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On a Common Mistake in the Description of the Photoelectric Effect

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The photoelectric effect is one of the key experiments taught during first- or second-year university and high school modern physics courses. It is usually the first experiment to introduce light quantization and the concept of photons as "packets of energy." Here, we want to point out a widespread mistake concerning the interpretation of the saturation current at constant light intensity that is found even in some classic hardback literature.[1] Although this is usually overlooked, it can weaken the conclusions a student can draw from the correct understanding of the experiment.

In the simplified experimental setup usually presented for the photoelectric effect (shown in Fig. 1), light composed of photons with frequency f and energy $E = h{\cdot}f$ impinges on a metallic cathode C from which photoelectrons are extracted with a distribution of kinetic energies. The emission of the photoelectrons is observed given that the photons have an energy E larger than the binding energy of the electrons in the cathode. This is called the work function of the material from where a cut-off frequency can be established. A tunable electrostatic potential V slows down or accelerates the emitted photoelectrons on their way (through vacuum) towards an anode A connected to an ammeter measuring the so-called photocurrent i.

In the explanation of the effect, the focus is usually on the dependence of the stopping potential V_0 (i.e., the maximum negative potential at which no photocurrent is measured) with the frequency of the light used. A plot like that shown in Fig. 2 is usually drawn to explain that, since $V_{0a} > V_{0b}$, the frequency of source "a" is higher than that of source "b". This is enough to explain the quantized character of light. Following this, it is usually pointed out that at positive potentials, because all emitted electrons are accelerated and reach the anode irrespective of their initial kinetic energy, the photocurrent saturates. This fact is customarily accompanied with the comment that the stopping potential V_0 does not depend on the intensity of the light. As a consequence, the saturation current is equal for sources with equal intensities, irrespective of the frequency. The explanation of saturation of the i-V curve is usually not carried any further because the quantization of light has already been illustrated. However, as the reader has possibly detected, in that last comment a mistake is made, one that potentially undermines the reached conclusion, i.e., the light quantization.

The mistake can be found in widespread modern physics course bibliography.[1] More informally, but nowadays equally important, a web image search with the keywords "photoelectric+effect+saturation" reveals not a single correct graph in the analyzed results, nor are the explanations found in the sources satisfactory.

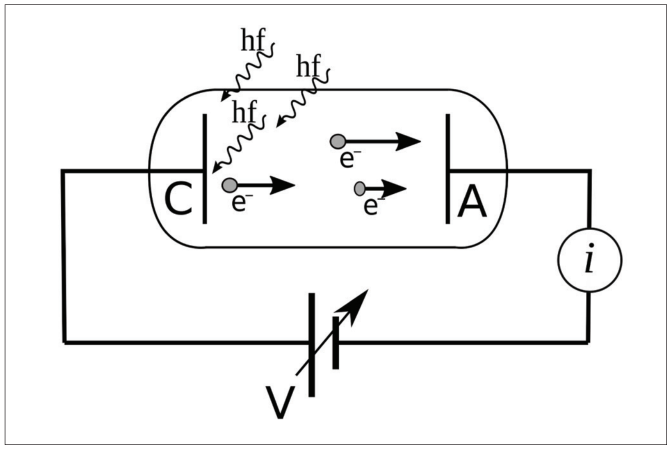

Fig. 1. Simplified experimental setup for the photoelectric effect. Photons with frequency *f* and energy *E* = *h·f* illuminate a cathode C from which photoelectrons are emitted, and a tunable potential *V* accelerates the emitted photoelectrons towards an anode A connected to an ammeter measuring the photocurrent *i*.

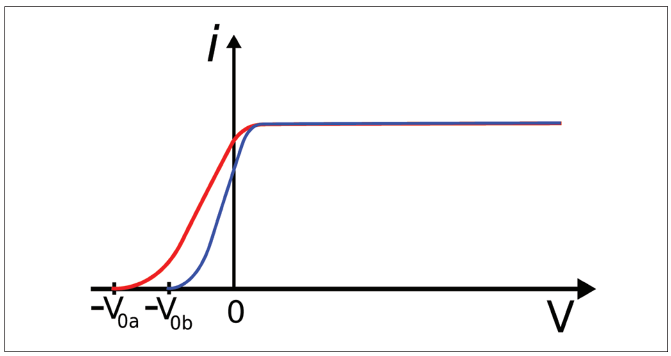

Fig. 2. Photocurrent vs. applied voltage plot usually employed during explanations. The frequency of the source a is higher than that of source b. The intensities, however, cannot be the same.

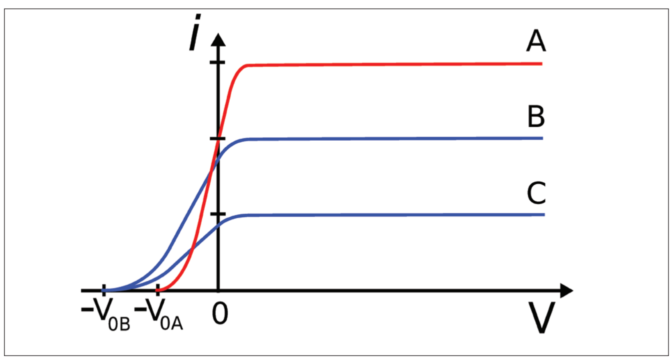

Fig. 3. Photocurrent vs. applied voltage plot for three light sources. Sources B and C have frequency f_B and intensities related by I_B=2·I_C. Source A has a frequency f_A=2/3·f_B and intensity I_A= I_B. The saturation currents are then i_A=3·i_C and i_B = 2·i_C.

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A correct explicit explanation could proceed as follows. From the point of view of the light quantization, the light intensity (irradiance) at the cathode is given by $I = n{\cdot}h{\cdot}f$, where n is the photon flux, i.e., the number of photons arriving at the cathode per unit of time and area. So, logically, sources with different frequencies but same intensities will differ in their n. On the assumption that each photon incident on the cathode (or a constant portion of them) extracts one electron contributing to the photocurrent $i = n{\cdot}e$ (where e is the electron charge), sources with different frequencies giving rise to the same saturation current must necessarily emit with different intensities. Only sources emitting the same photon flux will result in the same saturation photocurrent.

Precisely, this mix-up between light intensity and photon flux has to be made clear. This could be done, for example, as in Fig. 3, where the *i-V* curves of three different sources are sketched. Sources B and C have the same frequency f_B but different intensities being $I_B > I_C$ and, consequently, $n_B > n_C$. Source A emits at $f_A < f_B$ with $I_A = I_B$, which implies that $n_A > n_B$, which, in turn, results in a larger saturated photocurrent. These calculations can be worked out quantitatively (see caption of Fig. 3).

It must be noted that many books do not dig into the *i-V* relationship enough to present an interpretation of the saturation current in terms of the photon flux. Moreover, although not so explicitly as above, there exists literature where the saturation current is correctly treated and its importance highlighted. For example, A. B. Arons, in a book addressed to physics teachers,[2] suggests to inquire students about the light intensity-saturation current relationship in the way this paper describes. McKagan et al. developed and reported a freely available interactive simulation of the photoelectric effect.[3] They noted that "[t]he simulation behaves in [the] physically correct way, but it has caused some confusion among both students and instructors, who expect the number of photons to remain fixed [as the frequency is varied at constant light intensity]." The authors also mentioned a book where this mistake was reproduced (the last one in Ref. 1). Steinberg et al.[4] also developed a computer-based tutorial on the photoelectric effect and observed similar conceptual problems regarding the intensity-photon flux relation.

In conclusion, this somewhat naive but widespread error equals to mixing up two related but very different quantities (light intensity vs. photon flux) at a key moment when those concepts are being introduced to students. Correctly understanding the effect of intensity on the photocurrent is of great importance so that the adopted picture of light as packets of energy is not undermined. Moreover, digging into the explanation of the dependence of the saturated photocurrent on the light intensity enriches and widens the scope of the concepts studied in the photoelectric effect.

Acknowledgments

The author wants to thank E. Rojas for first mentioning the inconsistency between the class graphs and the *i-V* curves of some sources.

References

1. For example, the following figures and related text explanations all make the pointed-out mistake: Paul A. Tipler and Ralph A. Llewellyn, *Modern Physics*, 6th ed. (W. H. Freeman and Company, New York, 2012), Fig. 3.9; Hugh D. Young and Roger A. Freedman, *Sears and Zemansky's University Physics with Modern Physics*, Vol. 2, 12th ed. (Pearson, 2008), Fig. 38.5; Stephen T. Thornton and Andrew Rex, *Modern Physics for Scientists and Engineers*, 4th ed. (Brooks/Cole, Boston, 2013), Fig. 3.13; Arthur Beiser, *Concepts of Modern Physics*, 6th ed. (McGraw-Hill, New York, 2003), Fig. 2.11; R. Knight, *Physics for Scientists and Engineers* (Pearson, San Francisco, 2004), Fig. 38.3; note that this mistake is corrected in later editions of Knight.
2. Arnold B. Arons, *Teaching Introductory Physics* (Wiley, 1997), p. 288.
3. S. B. McKagan, W. Handley, K. K. Perkins, and C. E. Wieman, "A research-based curriculum for teaching the photoelectric effect," *Am. J. Phys.* **77**, 87–94 (Jan. 2009). The simulation is available at https://phet.colorado.edu/en/simulation/photoelectric (accessed in October 2018) as part of the PhET Interactive Simulations project at the University of Colorado Boulder.
4. R. N. Steinberg, G. E. Oberem, and L. C. McDermott, "Development of a computer-based tutorial on the photoelectric effect," *Am. J. Phys.* **64**, 1370–1379 (Nov. 1996).

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