

## 97 The photoelectric effect

*Subject:*

At school and university the photoelectric effect is demonstrated in order to prove the quantum nature of light. It allows for a simple measurement of Planck's constant with fairly good accuracy.

Fig. 1 shows the experiment schematically. Light is incident on a cathode that is made of a material with a low work function, typically an alkali metal.

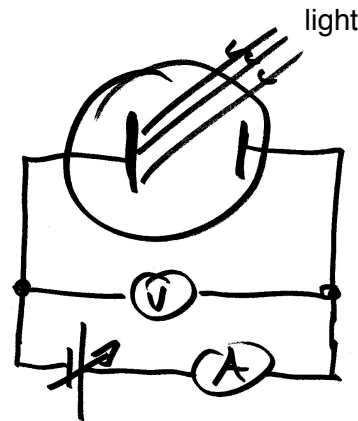


Fig. 1. The voltage is adjusted in such a way that the photocurrent gets zero.

The voltage is adjusted in such a way that the photocurrent becomes zero. For the interpretation Einstein's equation is used, which, written with modern symbols, reads:

$$E_{\text{kin}} = h \cdot f - W_{\text{A-cat}} . \quad (1)$$

Here  $h$  is Planck's constant,  $f$  is the frequency of the incident light and  $W_{\text{A-cat}}$  is the work function of the cathode material.

The emitted electrons lose a part of their energy within the cathode. Equation refers to those electrons that do not lose energy before leaving the surface of the cathode. Thus,  $E_{\text{kin}}$  represents this maximum kinetic energy.

Now, it is claimed that

$$E_{\text{kin}} = e \cdot U_{\text{max}} \quad (2)$$

where  $U_{\text{max}}$  is that voltage which has to be applied in order to get the electric current just zero, see for example [1, 2, 3, 4].

The experiment is carried out with light of several different wavelengths. Then,  $e \cdot U_{\text{max}}$  is plotted over the frequency of the incident light. One obtains a straight line, whose slope is Planck's constant  $h$ :

$$e \cdot U_{\text{max}} = h \cdot f - W_{\text{A-cat}} . \quad (3)$$

The point where the straight line cuts the vertical axis is, so it is said, the work function of the cathode material.

### Deficiencies:

Equation (2) is not correct. The voltage  $U_{\max}$ , that is measured in the experiment, does not correspond to the kinetic energy of equation (1). As a consequence, equation (3) is also wrong.

To understand why let us discuss a model system, Fig. 2a. We consider to containers L and R (left and right) with water. The height  $h_L$  of the edge of L above the water level of L is smaller than  $h_R$ , which is the height of the edge of R above the water level of R. We call  $\Delta h$  the difference of the water levels.

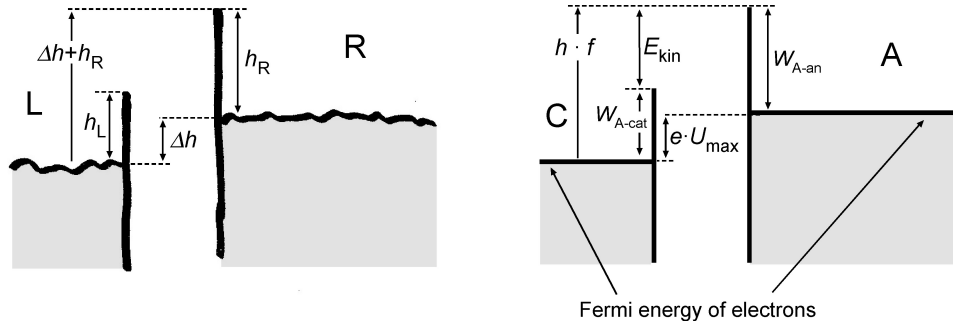


Fig. 2. (a) A portion of water of mass  $m$  is to be transferred from the container L at the left to container R at the right. For this process the energy  $m \cdot g \cdot (\Delta h + h_R)$  is needed. (b) An electron is to be transferred from the cathode C to the anode A. For this process the energy  $eU_{\max} + W_{A-an}$  is needed.

Now we want to transfer a water portion of mass  $m$  from L to R. The energy that is necessary for this operation is determined by the difference of the water level in L and the height of the edge of R:

$$\text{Minimum transfer energy} = m \cdot g \cdot (\Delta h + h_R) . \quad (4)$$

It is seen that height  $h_L$  does not enter into the result.

The similarity with the photoelectric effect is obvious. In Fig. 2b on the left side there is the cathode (C), on the right side the anode (A). The vertical direction corresponds to the energy of the electrons.

The water levels of Fig. 2a correspond to the Fermi energies (electrochemical potentials) of the electrons within the cathode or anode, respectively. The distance between the water level to the corresponding container edge corresponds to the work functions  $W_C$  and  $W_A$ , respectively. The minimum energy that is necessary to transfer a portion of water from one container to the other corresponds to the energy  $h \cdot f$  which a photon must at least have in order to transfer an electron from the cathode to the anode. One can see from the figure, that this energy can be expressed in two ways:

Either

$$h \cdot f = e \cdot U_{\max} + W_{A-an} \quad (5)$$

or

$$h \cdot f = E_{\text{kin}} + W_{A-cat} \quad (6)$$

From equation (5) we get

$$e \cdot U_{\max} = h \cdot f - W_{A-an} .$$

This expression is the analogue to equation (4). From equation (6) follows

$$E_{\text{kin}} = h \cdot f - W_{A-cat} .$$

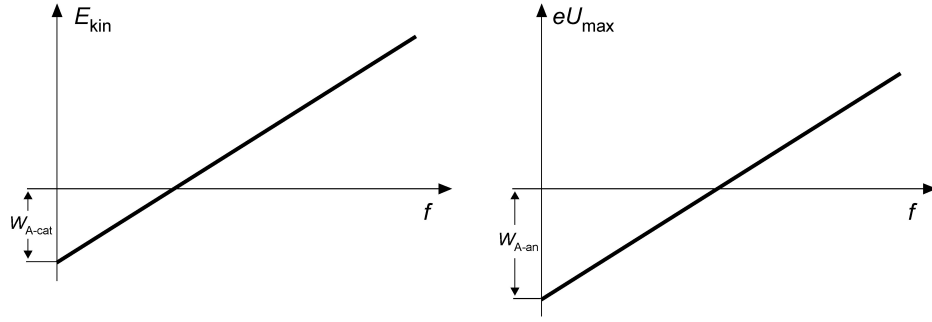


Fig. 3. (a) Kinetic energy over frequency of incident light. The section on the vertical axis is the workfunction of the cathode. (b) Maximum voltage times elementary charge over frequency of incident light. The section on the vertical axis is the workfunction of the anode.

The straight lines that correspond to the last two equations are represented in figure 3. In order to extract electrons from the cathode material (in order to have  $E_{\text{kin}} > 0$ ) the photon energy  $h \cdot f$  must be greater than the work function of the cathode, or  $f > W_{\text{A-cat}}/h$ .

The straight line of Fig. 3a is obtained from that of Fig. 3b by a translation in the direction of the vertical axis by  $W_{\text{A-an}} - W_{\text{A-cat}}$ . This difference of the work functions of anode and cathode corresponds to what is called the contact voltage  $U_C$  between the two materials, since we have:

$$e \cdot U_C = W_{\text{A-an}} - W_{\text{A-cat}} \quad (7)$$

In the majority of the books that we have consulted,  $e \cdot U_{\text{max}}$  is plotted as a function of the frequency, as in our Fig. 3b, the labeling of the axis' however was that of our Fig. 3a. We found a correct treatment of the subject only in Schpolski [5].

Even though one may follow our arguments, the following objections might arise: The experiment as it is carried out at the school or at the University lab, gives as a result the work function of the material of the cathode and not that of the anode. The latter would be much greater than the approximately 2 eV which are actually measured. The explanation for this strange behavior is that a small amount of Cesium (we suppose to have a Cesium cathode) has reached the surface of the anode. Actually the manufacturers of photocells advert to this effect. A sporadic covering of the anode's surface with Cesium is sufficient to allow all of the photoelectrons to enter into the anode material. Each spot of a material with a lower work function represents a potential minimum for the electrons so that the electrons voluntarily choose these locations to enter the anode material. According to the manufacturer's advice some photocells must be heated from time to time in order to clean the anode from the cathode material. Otherwise, the anode itself may begin to act as a source of photo electrons due to stray light.

Finally one might ask why the manufacturers make the cathode of a material with a small work function like Cesium, and why they do not use such a material for the anode. To answer this question we must remember what the photocells are produced for. Usually they are not made to enable physics teachers to measure Planck's constant. They are made to measure light intensities and for that purpose the applied voltage is in the other direction: not to stop the electrons but to extract them from the cathode. In order to be sensitive for light with long wavelengths the work function of the cathode must be small.

*Origin:*

Einstein's work on the effect is not an experimental work.

For a rather long time after his publication no experimental data were available. Einstein's was only interested in the explanation of the observation that the kinetic energy of the single electrons is independent of the light intensity, and that the number of the emitted electrons is proportional to the light intensity [6].

The effect was measured very thoroughly in the decades following Einstein's publication by various researchers. The most important work was done by Millikan [7, 8] and by Lukirsky and Priležeav [9]. Figure 4 is from the publication of Lukirsky et al. It shows the kinetic energy  $E_{\text{kin}}$  of the emitted electrons as a function of the frequency of the incident light. According to equation (1) the axis intercept (not shown in the figure) on the vertical axis is to within a factor  $e$  equal to the work function of the cathode. The authors obtained the kinetic energy by adding the contact voltage between cathode and anode to the measured voltage  $U_{\text{max}}$ . They (just as Millikan) had measured the contact voltage independently.

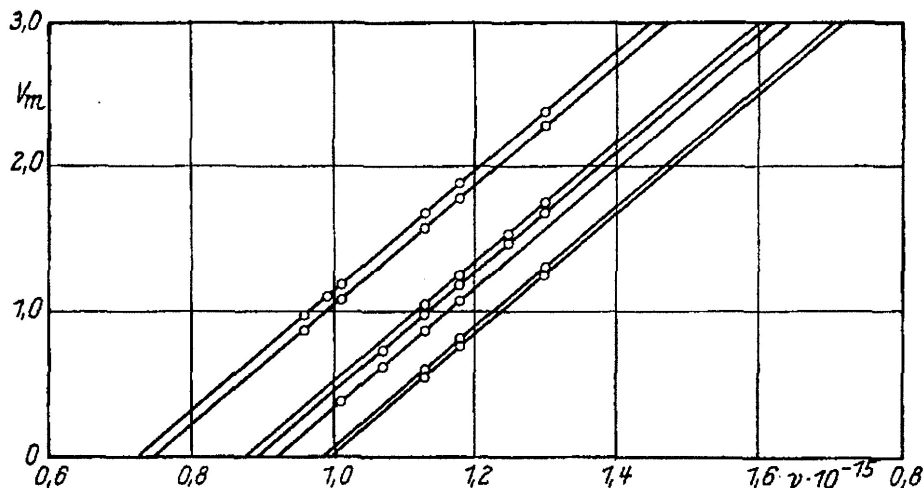


Fig. 10.

Die Geraden entsprechen den Metallen (von links gerechnet):  
Al, Zn, Sn, Ni, Cd, Cu, Pt.

Fig. 4. The original results from the work of Lukirsky and Priležeav [9]. Vertical axis:  $U_{\text{max}} + U_C$ , horizontal axis: Frequency of incident light.  $U_{\text{max}}$  is that voltage for which the photocurrent just gets zero,  $U_C$  is the contact voltage. The section on the vertical axis (not shown in the figure) would correspond to the workfunction of the cathode. If only  $U_{\text{max}}$  would be represented one would get the workfunction of the anode.

In many books a similar plot is found with the only difference that the vertical axis is said to correspond to  $e \cdot U_{\text{max}}$  (or  $U_{\text{max}}$ ), and that it is claimed that this is equal to the kinetic energy. In [2] the original graph of Lukirsky et al is reproduced in facsimile, but the lettering of the vertical axis has been changed into  $U_{\text{max}}$ .

How could such a transmission error come about? It is not implausible to identify the stopping voltage (times elementary charge) with the maximum kinetic energy. Who is not familiar with contact voltages may consider them as a perturbation that can be neglected for a first approach. Even Schpol-ski, who treats the subject very thoroughly suggests that the contact voltage

is a kind of killjoy. Of course, one can hold this point of view. But then one should abstain from interpreting the vertical axis intercept altogether, since what is called the cathode's work function is a quantity of the same kind as the difference of two such work functions, see equation (7).

Finally, the contact voltage is nothing else than the difference of the chemical potentials of the electrons in both materials. The chemical potential has nothing to do with the surface of the materials, and it is independent of whether the surfaces are clean or not. Thus the work function and the contact voltage are quantities that are just as respectable as other material properties like mass density or electric conductivity. Of course, the cleanliness of the surfaces does influence the results of the measurements, because if the surface is covered with dirt, one has to do with the chemical potential of the dirt instead of that of the bulk material.

Not only the origin of the error is interesting, but also the history of the vain efforts to correct it. In 1973 an article with the unambiguous title "Photoelectric effect, a common fundamental error" appeared in the English review *Physics Education* [10]. Three years later an article with the title "Concerning a widespread error in the description of the photoelectric effect" was published in the *American Journal of Physics* [11]. Its Authors seemed to ignore the British publication. In 1980 a similar article appeared in a German school science review with the featureless title "Work function and photoelectric effect" [12]. The author cites the American publication.

This story shows that an error can survive, even when a correction or revision is reminded. If the wrong idea is plausible and if its divulgation does not cause too much harm, it seems that a correction is impossible.

#### *Disposal:*

Three possibilities.

1. Explain the effect correctly, for instance with the water model shown above.
2. Abstain from interpreting the axis intercept.
3. Abstain completely from carrying out and interpreting the experiment. For a scientist in the year 1910 or 1920 the experiment was important, it was a key experiment. Fortunately the students today must not acquire their knowledge under the same difficult conditions as students at this ancient time. We now know how the story ends and we know an infinity of other experiments that can only be interpreted on the basis of the quantization of the interaction between light and matter. We know the Schrödinger equation and we are able to detect single photons with inexpensive material. No student will miss something in the understanding of physics when he or she did not see the photoelectric effect experimentally.

[1] *Gerthsen, Kneser and Vogel: Physik*, Springer-Verlag, Berlin 1977, p. 308

[2] *Stierstadt, K.: Physik der Materie*, VCH, Weinheim 1989, p. 489

[3] *Wichmann, E. H.: Quantum Physics*, Berkeley Physics Course, Volume 4, McGraw-Hill, New York 1971, p. 28-31

[4] *Hecht, E.: Optik*, Addison-Wesley, Bonn 1989, p. 571-574

[5] *Schpolski, E. W.*: Atomphysik, VEB Deutscher Verlag der Wissenschaften, Berlin 1972, p. 315-320

“Secondly, the curve is also displaced, as it happens in all similar cases, due to the contact potential, which is difficult to measure exactly. This as well as several other difficulties and sources of error are the reason why Einstein’s equation could not be verified properly at the beginning. Only Millikan succeeded in giving the experimental proof that had been pursued for a long time, and in determining  $h$  exactly, after lengthy preparations in whose course contradictions had to be disclosed and eliminated.”

[6] *Einstein, A.*: Über einen die Verwandlung des Lichts betreffenden heuristischen Gesichtspunkt (On a heuristic point of view about the creation and conversion of light), *Annalen der Physik* 322, Nr. 6, 1905, S. 132-148.

“If each energy quantum of the exciting light releases its energy independently from all others to the electrons, the distribution of velocities of the electrons, which means the quality of the generated cathode radiation, will be independent of the intensity of the exciting light; the number of electrons that exits the body, on the other hand, will, in otherwise equal circumstances, be proportional to the intensity of the exciting light.”

[7] *Millikan, R. A.*: Einstein’s Photoelectric Equation and Contact Electromotive Force, *Phys. Rev* 7, 1916, p. 18-32

[8] *Millikan, R. A.*: A Direct Photoelectric Determination of Planck’s “ $h$ ”, *Phys. Rev* 7, 1916, p. 355-388

[9] *Lukirsky, P., Priležev, S.*: Über den normalen Photoeffekt (On the normal photoelectric effect), *Zeitschrift für Physik* 49, 1928, p. 236-258. “If the axis of ordinate represents the values of  $V_2 + K$ , which are obtained by irradiating a given metal with light of various frequencies, and if the axis of abscissas represents the frequency  $\nu$ , we obtain a straight line whose tangent is equal to  $h/e$ . Since  $e$  is known we obtain the value of  $h$ .” (Here  $V_2$  stands for  $U_{\max}$ , and  $K$  the contact voltage.)

[10] *James, A. N.*: Photoelectric effect, a common fundamental error, *Phys. Ed.* 8, 1973, p. 382-384

[11] *Rudnick, J., Tannhauser, D. S.*: Concerning a widespread error in the description of the photoelectric effect, *Am. J. Phys.* 44, 1976, p. 796-798

[12] *Strnad, J.*: Die Austrittsarbeit beim Photoeffekt, *Praxis der Naturwissenschaften – Physik*, 1980, p. 343-344

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