using the dye fluorescein[7] in place of crystal violet. In this dye the absorption is much weaker, and the fringes behaved as if the cover glass had been coated in patches on its back with a glass of a higher index of refraction, so that dark fringes ran directly into bright fringes over the dye streaks.

Additional comments are in order on how the photograph of Fig. 3 was made. Individual cover glasses were selected for use on the basis of the relative uniformity of their fringe pattern. The crystal violet dye was applied in alcohol solution as thickly as possible with a cotton swab. The light from a mercury street lamp some fifty meters away was used together with a Wratten K2 filter (yellow). The use of this filter improved the visibility of the fringes by absorbing light from lines toward the blue end of the mercury spectrum. Exposures were for several seconds with Kodak Tri-X film. No lens was needed: the cover glass reflected light from the street lamp directly onto the film from a distance of about 10 cm. Extraneous light was excluded by a simple cardboard baffle. It was necessary to check that no interference pattern appeared beneath the dye streaks when the cover glass was viewed from behind. Otherwise it would not have been possible to distinguish the effect discussed here from shifts produced by reflection from the air side of the dye layer. Pictures using fluorescein were made in the same way. This dye was also applied in alcohol solution. Its hygroscopic properties made it more difficult to work with than crystal violet.

The interferometer described here is derived from a class of more refined instruments that have been used to study the optical properties of metals.[8–10] Although unsuited for quantitative measurements it demonstrates convincingly the scattering phase shift associated with the process of absorption.

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Concerning a widespread error in the description of the photoelectric effect

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The purpose of this note is to draw attention to a widespread error appearing in elementary physics textbooks. The error is connected with descriptions of Millikan's experiments on the photoelectric effect. The experiment is a classical one illustrated schematically in Fig. 1.

Light with a frequency ν is incident on the emitter (the emitter and collector are both metals, but are not necessarily the same kind of metal). Photoemitted electrons are picked up by the collector and detected as current by the ammeter. It is found that for every frequency that can stimulate a photocurrent with no applied back-voltage from the battery in the circuit, there exists a back-voltage just sufficient to cause the photocurrent to cease. This is called the stopping potential, V. Plotting eV vs ν (Fig. 2), one obtains a straight line described by the relation

$$eV = h\nu - \phi. \qquad (1)$$

The general form of (1) is in accord with Einstein's theory of photoemission.[1]

We have checked several elementary physics textbooks of recent vintage[2–8] in which the experiment is discussed; in all of them it is incorrectly claimed that ϕ in Eq. (1) equals the work function, ϕ_e, of the emitter, and therefore that ϕ_e can be directly measured by the setup of Fig. 1. The common argument is basically that, since an elec-

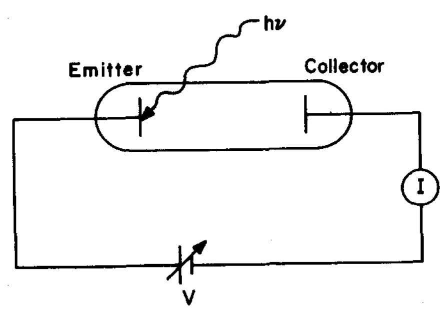

Fig. 1. Schematic illustration of Millikan's classical photoelectric effect experiment.

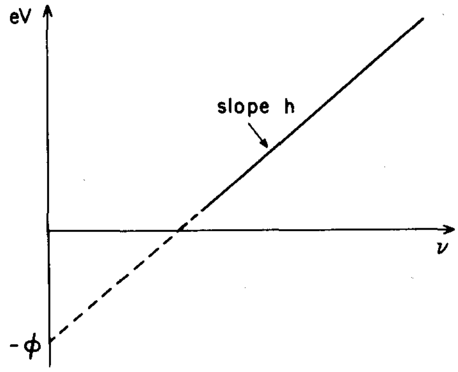

Fig. 2. Electronic charge times the stopping potential, eV, as determined in the experiment illustrated in Fig. 1, plotted versus the frequency ν of the incident light.

tron that has just left the emitter because of absorption of a photon of energy $h\nu$ can have a maximum kinetic energy $T_{\max} = h\nu - \phi_e$, therefore a back-voltage V given by

$$eV = T_{\max} = h\nu - \phi_e \tag{2}$$

will be required to prevent all electrons from reaching the collector.

We would like to show in a simple way that, while the expression for $T_{\max}$ is correct, Eq. (2) for the stopping potential is incorrect, and that ϕ in Eq. (1) is not ϕ_e but ϕ_c, the work function of the collector. Equation (1) should thus be written

$$eV = h\nu - \phi_c. \tag{3}$$

Since room temperature is a very low temperature as far as the electrons in a metal are concerned, we shall derive Eq. (3) for the case of zero temperature. This is a simpler case because then the difference between free energy and internal energy disappears. The derivation assumes no sophisticated knowledge of the behavior of electrons in metals and should therefore be suitable for an elementary undergraduate course.

Let us first consider the situation when $V = 0$ [Fig. 3(a)]. The maximum energy of electrons in the emitter and the collector must be the same since the electrodes are connected metallically. The hydrostatic case of communicating vessels can be used as a useful, though not completely accurate, analog. We shall take this common energy as the zero of energy. The work function of a metal is defined as the minimum energy necessary to transfer an electron from just inside the metal to just outside the metal. If the work functions of the emitter and the collector are different, then clearly an electron at rest just outside the emitter will have a different energy from an electron at rest just outside the collector. The difference in the energies of the electrons at rest just outside the two electrodes is called the contact potential difference (CPD). It is just equal to the difference in the two work functions.

When we insert a voltage (a battery) into the circuit, the maximum energy of the electrons in the two electrodes will not be the same any more. The difference between the energies at the two points A and D is by definition just the electronic charge times the applied voltage. Figure 3(b) is now appropriate.

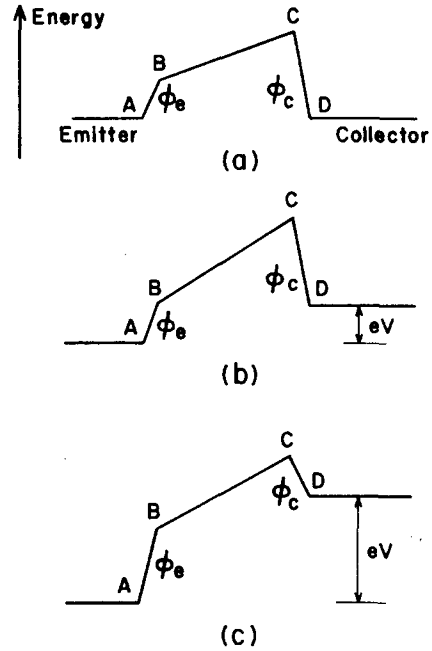

Fig. 3. Energy of an electron at various points in the phototube of Fig. 1: Maximum energy inside the emitter (A) and the collector (D) and minimum energy in the space between emitter and collector (line BC). ϕ_e and ϕ_c are the respective work functions. (a) No back-voltage applied, $\phi_e < \phi_c$; (b) finite back-voltage V applied, $\phi_e < \phi_c$; (c) same as (b) but with $\phi_e > \phi_c$.

It is seen that the current will cease when the applied voltage is such that the photon which is absorbed by an electron at point A in the emitter can supply the electron with just enough energy to surmount the point of highest energy. In Fig. 3(b) this is point C, which is at an energy $eV + \phi_c$ above that at point A. We therefore obtain immediately for the zero current condition $h\nu = eV + \phi_c$, which is Eq. (3). Thus we have shown that the experiment illustrated in Fig. 1 measures directly the work function of the collector. Figures 3(a) and 3(b) are drawn for the case $\phi_e < \phi_c$; for the case $\phi_e > \phi_c$, which leads to the same conclusion, see Fig. 3(c).

The correct version of Eq. (1) [i.e., Eq. (3)] is common knowledge among workers doing research in photoemission.[9] It is also presented in some texts on modern physics for third and fourth year students,[10–11] and in one very recent elementary textbook.[12] Interestingly, the correct interpretation of (1) was known to Millikan himself at the time of his pioneering work,[13] although it is not clear that he accepted it. In any case, the correct definition of ϕ in (1) does not affect his major result, which was the determination of h/e from the slope of the V-vs-ν line. Later,[14] he did explicitly accept Eq. (3) and verified it by performing a set of measurements using different emitters but the same collector.

The development of the incorrect interpretation is probably as follows: Before about 1940 the concept of work function was considered sufficiently unclear or difficult that elementary textbooks steered away from a detailed discussion of that aspect of Millikan's experiment. More recently, this concept has been regarded as simple enough to introduce in elementary physics texts. The reasoning which we have used, or any equivalent reasoning, is however not completely straightforward and the error generated by not thinking the situation through to its logical conclusion has propagated from one elementary textbook of modern physics to the other.

The error is clearly equivalent to disregarding the contact potential difference between two metals, which is just the difference $\phi_e - \phi_c$; that is, the stopping potential equals not $T_{\max}$ but equals $T_{\max} + (\phi_e - \phi_c)$.

Teachers of courses on modern physics should take note of this correction.

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Gauge and Lorentz transformations: An example

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The teaching of gauge transformations in undergraduate electricity and magnetism courses seems always to pose problems for most undergraduate students because of its inherent abstractness and the lack of examples of its use. Few books whether graduate or undergraduate dwell much on the subject and most of the time they treat the subject very briefly. This is mainly because after using the nonuniqueness of the potentials to select either the Lorentz or Coulomb gauge there is a lack of further examples. The author has found the following example to be illuminating to undergraduates at the junior and senior level in both the need and usefulness of the gauge transformation and a convenient way to introduce the concept of infinitesimal Lorentz transformations continuous with the identity.

Let us suppose that we have chosen the Coulomb gauge

$$\nabla' \cdot \mathbf{A}' = 0 \tag{1}$$

in an inertial frame S'. Then we ask the following question. How are the potentials ϕ' and $\mathbf{A}'$ of the Coulomb gauge in S' related to the potentials ϕ and $\mathbf{A}$ of the Coulomb gauge in an intertial frame S moving with constant velocity with respect to S'?

If the Lorentz transformations between the electromagnetic fields have already been developed the students will know that the Coulomb gauge is a noncovariant gauge, and if not the following will certainly illustrate this fact. Using infinitesimal Lorentz transformations because of their inherent simplicity, it is known that $\mathbf{A}'$ and ϕ' will transform into a set of potentials in S but not necessarily $\mathbf{A}$ and ϕ. Let the potentials in S related to $\mathbf{A}'$ and ϕ' by infinitesimal Lorentz transformations[1] be $\mathbf{A}''$ and ϕ''. Then

$$\mathbf{A}' = \mathbf{A}'' - \boldsymbol{\beta}\phi'', \tag{2}$$

$$\phi' = \phi'' - \boldsymbol{\beta} \cdot \mathbf{A}'', \tag{3}$$

where $\boldsymbol{\beta} = \mathbf{v}/c$ and $\mathbf{v}$ is the velocity of S' with respect to S. Using the transformation[2]

$$\nabla' \equiv \nabla + \frac{\boldsymbol{\beta}}{c}\frac{\partial}{\partial t} \tag{4}$$

and Eqs. (2) and (3), Eq. (1) to the first order in β becomes

$$\nabla \mathbf{A}'' + \boldsymbol{\beta} \cdot \left(\frac{1}{c}\frac{\partial \mathbf{A}''}{\partial t} - \nabla\phi''\right) = 0. \tag{5}$$

Obviously the transformed potentials do not belong to the Coulomb gauge in S, which is a good illustration of the noncovariant nature of the Coulomb gauge.

Now it is known that for two observers, one in S and one in S', each would have the right to choose the Coulomb gauge in his inertial frame to solve an electromagnetic problem common to both observers and each would obtain the correct solutions which are related to each other by the Lorentz transformations between electromagnetic fields so that there must exist potentials in S which belong to the Coulomb gauge. Therefore, $\mathbf{A}$ and ϕ must be related to $\mathbf{A}''$ and ϕ'' by a gauge transformation