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The Photoelectric Effect: Reconstructing the Story for the Physics Classroom

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Abstract The photoelectric effect is commonly used as the introductory topic for the study of quantum physics. However, a literature review reveals that besides various weaknesses and errors in the presentation of the history of the photoelectric effect, textbook presentations also contain incorrect presentations of the work function and the photon concept. In this paper, I present, in story form, five key episodes of the history of the photoelectric effect that are necessary for its accurate and adequate portrayal: (a) the discovery of the photoelectric effect, (b) the characterization of and initial explanation for the photoelectric effect, (c) Einstein's revolutionary paper on the light quantum and its explanation for the photoelectric effect, and his, eventually, receiving the Nobel Prize despite not having his hypothesis accepted, (d) Millikan's experimental verification of Einstein's photoelectric equation despite not accepting Einstein's hypothesis, and (e) Compton's measurements and his theoretical explanation which produced the ultimate acceptance of Einstein's hypothesis. The story, entitled "The Birth of the Photon Concept," has been tested in a classroom setting and is proposed as an essential component in the process of developing sound instructional materials.

> *All these fifty years of conscious brooding have brought me no nearer to the answer to the question, 'What are light quanta?' Nowadays every Tom, Dick and Harry [jeder Lump] thinks he knows it, but he is mistaken.* (Einstein 1951, p. 453)

1 Introduction

Virtually every first-year college or university physics textbook has in its introduction to quantum theory an elementary treatment of the photoelectric effect. In a recent, as yet, unpublished study, the author and colleagues (Niaz et al. 2009) analyzed over 100 introductory physics textbooks for their treatment of historical and philosophical aspects of the photoelectric effect. In the search for textbooks to use, only two were found that did not

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include the photoelectric effect. As early as 1932, Hughes and DuBridge wrote about Einstein's photoelectric equation that "this equation is perhaps the most important single equation in the whole quantum theory" (p. 7). A few years later, Wright (1937, p. 35) wrote that "Einstein's equation for the photoelectric effect … is the usual starting point for the presentation of quantum theory to undergraduates".

The photoelectric effect is, to this day, cited in the textbooks as confirmation of the existence of light-quanta or photons and this is seen as the main reason for its importance. Physics textbook author, Randall Knight (2004) writes about the photoelectric effect that "although this discovery might seem as a minor footnote in the history of science, it soon became a, or maybe *the*, pivotal event that opened the door to new ideas" (p. 1221, italics in original). It would seem, then, that the textbook treatment of the photoelectric effect, following in a long tradition of successive presentations, each one with some elements of improvement or new information, is an unproblematic aspect of physics teaching. However, when the literature on the history and teaching of the photoelectric effect is consulted, a different story emerges. The purpose of this paper is to examine the history and the scientific facts of the photoelectric effect and, thereby, provide a basis for the reformulation of its presentation in textbooks and popular media.

2 Literature Review

The literature that is relevant to the teaching of the photoelectric effect spans several areas. Several prominent and very useful articles deal with the history of the photoelectric effect and should be used as a basis for historical aspects of teaching materials. There are numerous articles that deal with misconceptions relating to the interpretation of the photoelectric effect. These misconceptions appear mainly in textbooks and other teaching materials. They deal with both experimental measurements and theoretical interpretations of the photoelectric effect. A major difficulty is identified in the interpretation of the work function in Einstein's photoelectric equation. Closely related to it is the proper interpretation of the "stopping potential" when measuring the photoelectric effect. Another major problematic issue is the interpretation of the photon concept, which is compounded by the progressive evolution of its understanding in the physics community. Surprisingly, a literature search yielded only one article (Steinberg et al. 1996) dealing explicitly with the teaching of the photoelectric effect as it relates to difficulties in student understanding.

This review is designed to provide a framework for the construction of an accurate and useful story which can be used as the historical background to any instructional approach. Such a presentation must not only be scientifically and historically accurate, but engaging, and it must qualify as a literary story (Klassen 2009). In addition, such a story must avoid implying any of the several conceptual errors that have been identified and, where possible, explicitly portray the correct interpretation.

2.1 The Quasi-History of the Photoelectric Effect

Kragh (1992) identifies six major areas that are a frequent part of quasi-historical presentations of the photoelectric effect in textbooks. Quasi-history may be defined as "a mythical history specially prepared for the indoctrination of certain methodological and didactic viewpoints" (Kragh 1992, p. 351). In the case of the photoelectric effect, these misconceptions or "myths" are that (a) Einstein's 1905 theory of the photoelectric effect relied on and was a natural extension of Planck's theory of 1900, which Einstein adopted and applied to the nature of light; (b) Einstein's 1905 paper was primarily a theory of the photoelectric effect; (c) the main aspect of Einstein's theory of the photoelectric effect was an explanation of experiments which showed that the kinetic energy of the photoelectrons depends linearly on the frequency of incident light but is independent of its intensity; (d) the experimental fact of the photoelectric effect is inexplicable without the photon hypothesis; (e) since there were no classical alternatives to Einstein's explanation, it was, of course, accepted; and (f) the final verification of Einstein's theory was provided by Millikan in his experiments of 1916 (Kragh 1992, p. 352). Stuewer (2006) goes on to show how Einstein's light-quantum hypothesis of 1905 was consistently rejected by the physics community and that it was only with Compton's theoretical explanation of the effect that the community reluctantly accepted the photon in 1925. A culmination of this early work on electrons and photons was presented at the 1927 Solvay Conference in Brussels (Bacciagaluppi and Valentini 2006). A useful summary of Einstein's paper and the circumstances surrounding the delay in its acceptance appears in Rigden's (2005) paper. Other useful historical information is contained in the various Nobel speeches of the era. An elaboration of the history based mainly on these resources will be presented later in this paper.

2.2 Interpretation of the Stopping Potential and Work Function

Einstein's photoelectric equation is normally written in textbooks as

$$eV = hv - \phi$$

where e is the electronic charge, V the potential difference across the phototube required to stop the most energetic photoelectrons, h is Planck's constant, v is the frequency of the incident light, and ϕ is the work function of the cathode in the phototube, which is assumed to be a metal. However, Einstein (1905) did not express his equation this way, preferring not to use Planck's constant explicitly, but rather expressing it in terms of other fundamental constants. Furthermore, as a review of the relevant literature reveals, the equation in this form is, at best, misleading, and at worst, simply incorrect.

Various authors (Keesing 1981, 2002; Rudnick and Tannhauser 1976; James 1973; Hodgson and Lambert 1975) have pointed out that the work function in a metal is measured relative to the Fermi energy of conduction electrons in the metal. Thus, when the photoelectric effect is measured at room temperature, the electrons have an energy distribution which makes it impossible to observe a distinct value of stopping potential at which the most energetic photoelectrons are stopped. Instead, the photocurrent approaches the voltage axis asymptotically. The direct observation of a stopping potential at room temperature along the lines predicted by Einstein's equation is thus rendered physically impossible according to Keesing (2002).

Furthermore, as soon as the phototube is connected into a real circuit, it is no longer the stopping potential which is being measured, but the stopping potential plus the difference in contact potentials of the various metallic junctions in the circuit. The net effect is that the work function in the photoelectric equation is not that of the cathode, but rather that of the anode! So, a more correct photoelectric equation would read

$$eV = hv - \phi_A$$

where ϕ_A is the work function of the anode or collector, which is not an intuitive result. Strictly speaking, if the photoelectric equation were to be formulated in the least problematic manner, assuming non-relativistic photoelectrons, it would read

$$\frac{1}{2} mv^2 = h\upsilon - \phi$$

where m is the mass of a photoelectron, v is the non-relativistic velocity of the most energetic electron, and ϕ is the minimum energy required to remove an electron from the surface of the metal in question. Even in this formulation, a temperature of $0K$ is assumed, otherwise a Fermi energy distribution for the velocities of the photoelectrons must be taken into account. Keesing remarks, in this context, that "several generations of undergraduate textbooks have made claims about the photoelectric effect which are not borne out by direct experiments and are incompatible with other branches of physics" (1981, p. 148). James (1973) suggests that "it is possible to discuss all the qualitative features of the photoelectric effect that lead to the idea of energy quanta without the detailed discussion of work functions … If one merely demands that removing an electron from a metal … uses up a certain energy … then photons have to be at least as energetic as this before the photoelectric effect releases electrons" (p. 384). Any elementary treatment of the photoelectric effect should, hence, not raise the issue of the work function but, simply, talk in general terms about the energy required to remove an electron from the metal.

2.3 Interpretation of the Photon Concept

Einstein used the term "light quantum" in his 1905 paper and the term "photon" was only invented in 1926 by the chemist Gilbert Lewis and used in his presentation of an incorrect theory of light quanta in which he proposed that photons were conserved and could be neither created or destroyed (Lewis 1926). The term was immediately adopted by the physics community when Compton began to use it in 1927. A number of authors (Strnad 1986; Kidd et al. 1989; Jones 1991; Milonni 1997; Freeman 1984; Armstrong 1983; Berger 1981; Stanley 1996) have pointed out that the concept of the photon has evolved since its initial proposal and that its interpretation, even today, is rather murky and even difficult. Twenty-five years ago, Freeman (1984) wrote that "the nature of the photon is an unresolved problem" (p. 11) and varying viewpoints still persist (Zeilinger et al. 2005; Roychoudhuri and Tirfessa 2006; Sulcs 2003; Gunther and Beretta 2005). Today, it would be uncontroversial to say that photons "are not particles like baseballs or shot; and the photon is not a return to Newton's corpuscular theory of light" (Armstrong 1983, p. 104) contrary to what is stated in some textbooks. Zeilinger et al. (2005) who are proponents of the photon, portray an instrumentalist account of the photon when they write:

> One might be tempted, as was Einstein, to consider the photon as being localized at some place with us just not knowing the place. But whenever we talk about a particle, or more specifically, a photon, we should only mean that which a 'click in the detector' refers to. (p. 233)

Whether one takes an instrumentalist or realist position, the interpretation of the photon is challenging; moreover, it is held by many that it is not necessary to have photons in order to explain the photoelectric effect successfully (Strnad 1986; Milonni 1997). In my conversations with colleagues who teach advanced undergraduate physics, I have learned that, even today, they use a semi-classical model to derive the photoelectric effect in their classes. However, the photon *per se*, can only be understood, and only partially at that, by a thorough understanding of quantum electrodynamics.

What, then, is one to say to students when they are being introduced to quantum mechanics? It should be made clear that the behavior of photons between the emitter and detector is not known but that we only know their quantum mechanical behavior when they are detected. Strnad recommends that

> [a]t the introductory level it is best to consider photons in the discussion of the photoelectric effect as energy quanta and in the discussion of the Compton effect as energy and momentum quanta, to say nothing about their position and avoiding as far as possible the analogy with electrons. (1986, p. 650)

The dominant picture of photons as “particles of light” is misleading, as it implies the localization and motion of particles of light between the emitter and detector of the light, even though such motion is not defined. What should be emphasized, rather, is the quantum mechanical nature of the *interaction* of light with matter.

The situation vis-à-vis the concept of the photon is much more complex than can be portrayed in a short summary such as this, and a thorough discussion of the various aspects would surely require a large volume. However, the few main points that have been discussed here will serve to guide the writing of introductory materials.

2.4 Student Difficulties with the Photoelectric Effect

It would seem that with the complexities mentioned here and given the misleading nature of much of the existing instructional material, students would be expected to experience difficulties in understanding the photoelectric effect. Surprisingly, not much has been written about the matter. Only Steinberg et al. (1996) outline a study in which students had difficulty interpreting the photoelectric experiment in terms of the photon model for light. In the study a tutorial was designed to address the problem. However, this study does not address the difficulties with the concepts themselves.

3 Reconstructing the Story of the Photoelectric Effect

As has been outlined in the literature review, many of the portrayals of the photoelectric effect suffer from inclusion of quasi-history and a partially wrong portrayal of the concepts, themselves. In order to facilitate the teaching of the introduction to quantum mechanics in a first-year university class, the author developed an accurate story to weave through the instruction. The historical and scientific sources for the story are contained in the literature review, above. Additional sources are cited, below. The story consists of five episodes that correspond to natural divisions in the development of the photoelectric effect. Usually, historical treatments of the photoelectric effect do not make a strong connection to the Compton Effect, but this is necessary, since the photon concept was not accepted until Compton formulated his explanation for the effect. The five episodes as presented here are (a) the discovery of the photoelectric effect, (b) the characterization of and initial explanation for the photoelectric effect, (c) Einstein’s revolutionary paper on the light quantum and its explanation for the photoelectric effect, and his, eventually, receiving the Nobel Prize despite not having his hypothesis accepted, (d) Millikan’s experimental verification of Einstein’s photoelectric equation despite not accepting Einstein’s hypothesis, and (e) Compton’s measurements and his theoretical explanation which produced the ultimate acceptance of Einstein’s hypothesis. I have entitled the story “The Birth of the Photon Concept”.

This story has been presented four times to the author’s first-year university physics class where it was well-received. In practice, the story is integrated with instruction, which includes live demonstrations, whole-class concept quizzes, chalkboard illustrations, and worked examples. In the presentation of the story below, commentary has been inserted as an indented block to separate it from the text of the story as it should be presented to students.

3.1 Hertz Stumbles on Something Important

> The story of the photoelectric effect must begin with the discovery of the effect. In the story, the relationships among the protagonists should be featured in order to re-introduce the humanistic element, which is, for the most part, not present in textbook presentations. Some relevant details can be found in Bryant (1998) and Acolyte Science (2008). Stories should, where possible, contain elements of suspense. At the beginning, I have chosen to withhold the identity of Hertz, naming him only when he makes the important discovery of radio waves.

The story begins in the 1880s with a 30-year-old physics professor in Germany—Heinrich, or Heinz as we shall call him—who had just been appointed Professor at the University of Karlsruhe. Heinz's doctoral supervisor had been the famous physicist, Helmholtz. Although Heinz was no longer his student, Helmholtz had ambitions for him. There was a problem prize in physics to be won from the Berlin Academy of Science, which Helmholtz wished that Heinz would tackle. The problem dealt with the experimental verification of an aspect of Maxwell's proposals on electromagnetism. Heinz was not much interested in winning the prize, but he was fascinated by Maxwell's theory, wondering whether the equations could be interpreted to yield electromagnetic waves that traveled through space. So, he took up Helmholtz's problem, but not his challenge, and developed an idea which resulted in an experimental demonstration of what was soon to be called "radio waves".

Heinz's demonstration worked essentially by connecting an oscillating high-voltage coil to a circuit in which it produced a series of sparks across a gap so as to cause the voltage to switch rapidly across an antenna. At the other end of the room, he placed a copper wire loop interrupted with a small copper sphere close to a pointed end of the wire. To everyone's amazement, small sparks jumped across the gap in the loop even though there was no physical connection between the antenna and the loop, located at opposite ends of a large room. And this is how, at the age of 31, Heinrich Hertz instantly became famous as the discoverer of radio waves. Hertz might have had a long and distinguished career, but, sadly, his life was cut short when at the age of 36 he died of a blood disease.

During his first series of experiments with radio waves, Hertz ran into a most curious phenomenon. He noticed that when he placed a shield over the detector coil to see the spark better in the dark, the size of the spark decreased. Even if he placed a plate of glass in front of the detector coil, the size of the spark still decreased. Knowing that, unlike ordinary glass, quartz transmits ultraviolet light, Hertz substituted a quartz plate for the glass. Now the spark retained its original size. It was a curious phenomenon, indeed!

In all his work, Hertz was assisted by his students. One student, in particular, Wilhelm Hallwachs, had an idea for transforming Hertz's curious result into a systematic experiment. He took a piece of pure zinc and attached it to an electrometer. Then he … but instead of describing what he did, let's do it ourselves and see if we can figure out what is going on.

> A live demonstration of the photoelectric effect similar to what was done by Hallwachs follows. Questions that should be raised as a result of the demonstration are (a) What properties of the phenomenon demonstrated did you observe? and (b)

> Do you [the students] have any (tentative) explanations (with reasons) for what you observe? The story should be concluded with a summary of Hallwach's observations, as follows.

Hallwachs concluded that when the electroscope is negatively charged, then this charge dissipates immediately and quickly under the influence of light on the zinc plate and that the light only has this effect if it has a strong ultra-violet component. However, when the electroscope is positively charged, then this charge dissipates very slowly, even under the influence of light shining on the zinc plate.

3.2 Physicists Investigate the New Phenomenon

> During the period between the initial discovery of the photoelectric effect and Einstein's 1905 paper, the phenomenon was investigated by prominent physicists. Students should realize that good experimental work was done at this early stage and that satisfactory theoretical explanations were put forward. These investigations established the main features of the photoelectric effect which should serve to help students understand the phenomenological aspects quite thoroughly.

The new phenomenon, which became known as the photoelectric effect, generated much interest in the physics community, but was seen as only one of the many new phenomena which needed to be explained by the theories of physics of the day.

Two prominent physicists, in particular, paid attention to the new effect. One was Sir J. J. Thomson of England and the other was Philipp von Lenard of Germany. Thomson was trying to establish the nature of the fundamental negative charge of electricity which he called "corpuscles", but which were commonly known as "cathode rays" and which we now know as the electron. Beams of the negative "rays" had been studied by physicists for some time. Many physicists did not believe that cathode rays were particulate in nature, but Thomson was certain that they were. In 1899, Thomson subjected the "negative electricity" emitted from metal plates under the influence of ultraviolet light to the same analysis as cathode rays. His conclusion was that these, too, were "corpuscles" or, as they were soon to become known, electrons.

Lenard set out to investigate the nature of the photoelectric effect even more thoroughly. By 1902, he had found, to his surprise, that only the number of electrons given off, but not their energy, was affected by the intensity of the light. But, most surprising of all, Lenard found that the energy of the electrons depended on the wavelength of the light and that shorter wavelength light tended to yield faster electrons. However, Lenard was unable to develop adequate experimental conditions to determine in what way this effect varied. In 1905, Lenard was awarded the Nobel Prize for his work on cathode rays. The next year, Thomson received the prize for his work on the electron. Although the photoelectric effect was, to some degree, puzzling, Lenard and other physicists used existing theories of physics to devise good explanations for it. Basically, they reasoned that since the electrons are ejected immediately when the light hits and since they have energy which does not depend on the intensity of the light, their energy must originate inside the atom. All that the light does is trigger the release of the electrons. Since the structure of the atom was not known at the time, their explanation was quite reasonable although not very detailed.

At this point, diagrams should be employed to explain in greater detail Lenard's experiments and what it was that he observed. Questions that students should address are (a) What further characteristics of the photoelectric effect (beyond those uncovered by

Hallwachs) were revealed by Lenard's work? And (b) Does Lenard's explanation for the photoelectric effect seem reasonable?

3.3 Einstein has a Revolutionary Idea Which is Rejected

> The next episode is the important story surrounding Einstein's 1905 paper. Following the advice gathered from the literature review, I have taken the liberty of removing several words from Einstein's revolutionary statement, namely, that light quanta "are localized points in space, which move without dividing"(Einstein 1905, p. 2). This aspect, according to the literature cited, creates a picture of photons which is not consistent with what is currently believed. Furthermore, it must be explained that when a circuit is constructed to illustrate Einstein's equation that the quantity usually identified with the work function is no longer the actual work function attributed to Einstein. Lastly, it should be pointed out that Einstein received virtually no support for his light quantum hypothesis for about 20 years and that even his being awarded the Nobel Prize was controversial.

In the next few years, much work was done on the photoelectric effect. The youthful Albert Einstein read about it, but his mind was on other things. He wondered how it could be that light, which is considered a wave, can interact with an atom which exists at only a point. His thoughts along these lines culminated in his famous paper of 1905, "On a Heuristic Point of View Concerning the Production and Transformation of Light". In it, he makes one of the most revolutionary statements in the history of physics: "…the energy of a light ray spreading out from a point source is not continuously distributed over an increasing space but consists of a finite number of energy quanta which … can only be produced and absorbed as complete units" (Einstein 1905, p. 2). These "energy quanta" eventually became known as photons. Einstein predicted that his light quanta each had energy that was a multiple of the frequency, v (the Greek letter, nhu). The constant could easily be worked out to be equal to Planck's constant, h, but Einstein chose not to use that notation. Einstein borrowed the concept of h, from Planck's recently-published concept of a collection of oscillators inside a heated body, but applied it, instead, to individual oscillators, in this case light quanta. Einstein listed three ways in which his hypothesis could be tested. One was a model of the photoelectric effect. Einstein claimed that it was possible for one light quantum to be absorbed by a single electron, imparting to it all its energy. If the electron is near the surface, some of its new-found energy will be lost in moving to the surface and escaping any electrical forces at the surface, requiring a quantity of energy, (designated by the Greek letter, phi), which is a property of the metal itself. The remaining energy, E, is observed as the kinetic energy, ½ mv^2 of the electron as it is ejected from the surface of the metal. The energies of the electrons so ejected will have a maximum value, since some may originate from beneath the surface and others (with maximum energy) originate exactly at the surface. The governing relationship is, then, very simply

$$E = hv - \phi,$$

where it is understood that E is the *maximum* energy of ejected electrons. If the electrons (which have a charge, e) are stopped by applying a negative repelling or stopping voltage of value V to the collector, then the relation becomes

$$eV = hv - \phi_C.$$

In this relationship the energy to remove the electron from the metal, ϕ, is replaced by a composite value, $\phi_{C,}$ which is a property of the circuit as a whole. Einstein wrote, in his 1905 paper, that "if the derived formula is correct, then [the stopping potential], when represented in Cartesian coordinates as a function of the frequency of the incident light, must be a straight line whose slope is independent of the nature of the emitting substance" (Einstein 1905, p. 14).

Einstein's light quantum was disdainfully rejected by the physics community. Max Planck, when nominating Einstein for membership in the Prussian Academy of Science in Berlin in 1913, felt that he had to defend Einstein in his nomination letter by writing "that [Einstein] sometimes, as for instance in his hypothesis on light quanta, … may have gone overboard in his speculations should not be held too much against him" (Kirsten and Körber 1975, p. 201). Even though Einstein's hypothesis was almost universally rejected, he wrote to his friend, Michelle Besso, that the existence of "the light quantum is practically certain" (Einstein 1916). In 1921, when Einstein was to receive his Nobel Prize, the Royal Swedish Academy of Sciences, which awards the prize, was caught in a dilemma, as they did not believe in Einstein's special theory of relativity, so they included the photoelectric effect in the prize when they awarded it the next year. However, they did not believe in the quantization of light either! In his Nobel Prize speech, also in the next year, Niels Bohr, who had formulated the first quantized theory of the atom, expressed his disregard for the light quantum concept by saying, "The hypothesis of light quanta… is not able to throw light on the nature of radiation" (Bohr 1922, p. 14).

> At this point, Einstein's equation should be discussed by plotting it on a graph. Questions that students should address are (a) What fundamental quantities can be determined from the graph? and (b) What are the main practical problems in measuring the photoelectric effect? The problem of surface contamination and oxidation may be raised. It would help to remind students that in the demonstration of the photoelectric effect in class, the sample had to be cleaned with emery cloth before using it.

3.4 Millikan Fails to Disprove Einstein but Gets the Nobel Prize

> In discussing the contribution of Millikan to the understanding of the photoelectric effect, it should be made clear that Millikan set out to disprove Einstein, and even when he confirmed Einstein's equation exactly, he did not accept Einstein's light quantum hypothesis. In addition, Millikan's restatement of the trigger hypothesis in his 1916 paper can be used to show students that viable theories for the photoelectric effect other than Einstein's hypothesis existed.

Chicago physicist, Robert Millikan, did not accept Einstein's light quantum hypothesis. He saw it as an attack on the wave theory of light. From 1912 to 1915 Millikan put all his efforts into measuring the photoelectric effect. A major difficulty was posed by the rapid oxidation of the metallic surfaces. To solve that problem, Millikan devised a technique for scraping clean the metal surfaces inside the vacuum tube which he described as a small "machine shop *in vacuo*" (Millikan 1950, p. 103). By 1915 it had become clear to Millikan that he had verified Einstein's equation exactly. He published his results in 1916, describing Einstein's light quantum hypothesis as a "bold, not to say reckless, hypothesis of an electro-magnetic light corpuscle of energy $h\nu$, which flies in the face of thoroughly established facts of interference" and which "now has been pretty generally abandoned"

(Millikan 1950, p. 355). Millikan, who was not a theorist, paraphrased the theories explaining the photoelectric effect in his paper. He wrote that the photosensitive metal must contain oscillators of all frequencies that are at all times loading up to the energy value $h\nu$. A few of them will be in tune with the frequency ν_0 of the incident radiation and thus will absorb energy until it reaches the critical value $h\nu_0$ at which time an explosion will occur and the electron will be shot out from the atom. Millikan's theoretical explanation was known as the trigger hypothesis and had been popular since Lenard.[1] By this time, everyone was beginning to realize that the trigger hypothesis was not a very satisfactory explanation, but they chose to live with it rather than accept Einstein's hypothesis. So, Millikan, albeit failing to disprove Einstein's equation, was able to measure h to within 0.5% of the value proposed by Planck. His consolation was that he received the Nobel Prize for his work on both the photoelectric effect and on determining the value of the electronic charge, in 1923.

> At this point, students should be ready to work textbook type problems on the photoelectric effect. However, the instructor should take the student through some typical problems so as to relate them to relevant aspects of what has been discussed about the photoelectric effect, so far.

3.5 Einstein's Idea is Rejected, but Compton Comes to the Rescue

> Students will be entering into a state of disequilibrium by now, as Einstein's hypothesis has still not been accepted by the physics community. At this point, the story of Compton's contribution, as portrayed in Stuewer (2006), can be used to bring a satisfactory resolution to the story.

Even though Einstein had received the Nobel Prize in 1922, physicists did not accept his photon concept. Almost the only one believing Einstein was his friend, Paul Ehrenfest. It was at this time that Arthur Compton began his experimental work in physics, first in St. Louis in 1920 and then in Chicago in 1923. Compton began to investigate the curious behavior of X-rays when projected at an aluminum target. Physicists had noticed that the absorption factor of the X-rays was lower than it should be. Compton began to consider various explanations for the anomalous absorption, including the speculation that the X-rays were being diffracted like light by the electrons in the aluminum atoms. The problem with Compton's explanation was that it required the electron to be almost as large as the atom itself. Other physicists were not impressed with the explanation, and Compton began to look for other reasons for the X-ray behavior. For one thing, he began to look more closely at the energies of the X-rays after they left the aluminum target. The energy of the X-rays decreased (or their wavelength increased) with the angle of emergence from the target. Finally, in 1923, Compton began to formulate a revolutionary explanation that worked. He observed with ever greater precision how the X-ray energy varied as it emerged from the target. Compton explained the change in wavelength (or energy) as the result of a billiard-ball-like collision of an X-ray quantum with a nearly-free electron in the target. In Compton's picture, both energy and momentum were perfectly conserved in the collision. At any given angle of emergence of the X-ray, only one wavelength was observed and the value shifted downward as the angle increased. Compton's billiard-ball explanation was somewhat complicated by the rather high energy of the electrons after their collision with the X-rays, which necessitated using a relativistic expression for the

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[1] For a discussion of another theory of the photoelectric effect, that of Richardson, see Katzir 2006.

electron momentum. When Compton put it all together, however, the resulting expression was amazingly simple:

$$\lambda' - \lambda_0 = \frac{h}{m_e c}(1 - \cos\theta)$$

where λ' is the wavelength of the X-ray emerging at an angle θ, λ_0 is the incident wavelength, h is Planck's constant, m_e the mass of the electron, and c is the speed of light in a vacuum. Niels Bohr, who had recently received the Nobel Prize for his work on the structure of the atom, would not accept Compton's explanation. He devised experiments to attempt to disprove Compton's theory by trying to show that the Compton Effect was only an average over many X-ray-electron interactions. However, by 1925 several experiments had been done that proved fairly conclusively that energy and momentum were conserved for each X-ray and electron pair separately. When Bohr learned of these results, he wrote to his friend, "It seems … that there is nothing else to do than to give our … efforts as honorable a funeral as possible" (Bohr 1925, p. 82).

In 1926 the word "photon" was invented for the light quantum. Compton's experiment and his theory to explain it served to provide convincing support for Einstein's photon hypothesis, and physicists generally accepted it at that time. Einstein wrote to his friend, Ehrenfest, "We both had no doubts about it" (Einstein 1925, p. 35). Some would say that Compton's experiment and theory was the definitive factor in the movement to the new physics of quantum mechanics. It was, certainly, the definitive factor in the acceptance of the photon concept.

> At this point, students should be invited to discuss the importance of Compton's work both for the acceptance of Einstein's photon hypothesis and the movement to the new quantum mechanics. The stage has been set for moving to the next topic in the course, which is, commonly, the wave nature of matter.

4 Concluding Remarks

As an example of the pervasiveness of pseudo or mythical histories of science, I refer to the popular and widely-used video series, *The Mechanical Universe and Beyond*. In episode 24, the topic "Particles and Waves" is introduced. In interpreting Robert Millikan's experiments performed up to 1916 to measure the photoelectric effect, the narrator of the video states:

> When he measured the energies of electrons ejected from various metals by different frequencies of light, Millikan verified that while each metal has a different work function, Planck's constant has the same universal value for all of them. But this explanation of the photoelectric effect not only confirmed Planck's theory, it showed directly that bundles of energy already exist in the electromagnetic field. (California Institute of Technology 1987).

However, as we have already established, this popular presentation misrepresents Millikan's motivation and his contribution. Initially, Millikan did not set out to verify, even indirectly, Planck's radiation formula or Einstein's light quantum hypothesis, which he did not accept until some time later. He simply sought to establish the mathematical form of the relationship between ejected electron maximum energy and incident light frequency, not any particular theory behind the relationship (Kragh 1992). Helge Kragh agrees with

Thomas Kuhn that such quasi-histories of science are intended to “make students believe that they are participants in a grand historical tradition which has progressed cumulatively and according to definite methodological norms” (Kragh 1992, p. 359).

My recounting of the story and raising probing questions as the problematic aspects emerge highlights the weakness of teaching science in a decontextualized and predictable fashion. In presenting the science story as it evolved historically, I have shown that science does not progress in the fashion in which it is stereotypically presented in science curricula and textbooks. I have shown that scientific discoveries are messy and that scientific theories do not arise in a neat and orderly sequence or even, necessarily, lead to better theories. By simplifying and misrepresenting the nature of scientific discoveries in isolation, we may, in fact, produce the very thing that we, as science teachers, want to avoid. Pretending that the answers to big questions were resolved in an uncomplicated, problem-free progression destroys or prevents the very engagement and questioning of students that we hope to stimulate. As American satirist H. L. Mencken once wrote, “there is always an easy solution to every human problem—neat, plausible, and wrong” (Mencken 1917, p. 443).

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