Toward Understanding Student Conceptions of the Photoelectric Effect

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The photoelectric effect is part of a group of phenomena that provide the experimental basis for the photon model of light. Most students pursuing a degree in physics or a related field first study the photoelectric effect and the photon model of light in a "modern physics" course following directly after the introductory physics sequence. It has been documented that many students have trouble understanding the photoelectric effect itself, and its connection to the photon model of light. In an attempt to better understand student preconceptions and misconceptions of this topic, we conducted a study of students in a modern physics class at California State University, San Marcos. In this paper we will provide preliminary results of our research with specific emphasis on the knowledge base required to understand the photoelectric effect.

Introduction

In this paper we report the initial results of a study of student learning of the photoelectric effect and the photon model of light conducted during the 2002-2003 academic year at the California State University San Marcos. The study took place in the modern physics portion of a third semester introductory calculus based physics course. The majority of the students were juniors majoring in computer science and the total course size was 14 students. The study used pre/posttest results, recordings of student discourse during laboratories on the photoelectric effect, and student usage data from a computer tutorial. Preliminary analysis of these data offers a picture of student preconceptions and learning processes on the photoelectric effect and the photon nature of light.

Study Methods

At California State University San Marcos, modern physics is taught during the third semester of the introductory physics sequence. The last ten of the fifteen weeks of this semester-long course are devoted to the study of modern physics, and the photoelectric effect is encountered in about the eighth week of instruction, immediately after the topic of relativity. The photoelectric effect and the photon model of light were topics in two lectures, and the topic of two of the two and-a-half hour laboratories. The first of these laboratories required students to use the program *Photoelectric Tutor* as part of the tutorials in Redish et.al.'s *A New Model Course in Applied Quantum Physics* [1].

As part of our study of student understanding of the photon nature of light, we administered a pretest on student understandings of the photon model of light prior to instruction. The test was composed of three questions aimed at (1) students understanding of the classical model of the interaction of light with matter, (2) the circuitry involved in the photoelectric effect experiment, and (3) the students' prior understandings concerning the photon nature of light. Copies of the questions used can be found in the Appendix.

In order to gain insight into the evolution of student understandings and the usefulness of the curriculum, we tape recorded and transcribed the conversations of two groups of students as they completed the first tutorial in *A New Model Course in Applied Quantum Physics.* This tutorial used the commercially available program *Photoelectric Tutor* [2], developed by Graham Oberem and Richard Steinberg. We also recorded student conversations during the laboratory the following week, where students completed a series of laboratory activities using the photoelectric effect experimental apparatus [3].

Due to the design of the computer tutorial, we were also able to collect data on student usage of the program. The program requires the students to produce graphs of current versus voltage for a photoelectric tube lit by monochromatic beam of light. Since the program records the I vs. V plots that the students produce, along with their responses to prompts intended to scaffold their understanding of the shape and features of the correct plot, the stored data of student interaction with the program provide a unique method of gaining insight into the evolution of student understanding as they use the program.

To capture the changes in student understandings, a posttest identical to the pretest was administered three weeks after instruction on the photoelectric effect was completed.

Results of Pre/Posttest

The questions on the pre/posttest (see Appendix) were free response that called for explanations in the answers. The responses were sorted on the basis of similarity of models used in the student's explanations. The results were then grouped into four general categories that we labeled excellent, very good, satisfactory and unacceptable based on how well the specifics of the student's models corresponded to the physical models involved. An excellent, very good, or satisfactory response was deemed as acceptably close to the actual physical model.

Analysis of the pretest results found that the majority of the students could not determine the current-voltage relationship from the traditional photoelectric effect circuit diagram prior to instruction, even when the freeing of electrons in the phototube was given. To answer this question correctly on the pretest, only knowledge of electromagnetism and electric circuits was required. Nonetheless, the analysis of student pretest results showed that only 2 of the 11 students could come up with a satisfactory current voltage relationship prior to instruction. Of the 2 that had at least a somewhat satisfactory current-voltage relationship, neither of the responses was completely correct.

The posttest results showed a marked improvement in student understanding of the circuit diagram with 10 of the 14 posttest respondents answering the question at least satisfactorily. 5 of these 10 responses were excellent, while 4 were very good responses.

To probe student understanding of the classical wave model of light, the students were asked to predict the effects of a single frequency light on a metal, according to the classical model of light. Prior to instruction, 7 of the 11 respondents were able to give an acceptable response to this question. All of these 7 mentioned the heating of the metal or motion of the electrons in the metal. In a follow-up to this question, the students were asked how they could change the light source in terms of the classical model of light so as to free electrons from the surface of the metal. Only 3 of the 11 respondents were able to give an acceptable response, and all 3 mentioned increasing the intensity of the light in order to provide more energy to the electrons.

Comparisons of the pretest results with the posttest results show marked improvements in student understanding of the photon model of light as pertains to the photoelectric effect. When asked prior to instruction to explain why increasing the frequency of the incident light beam would cause the ejection of electrons, only 2 of the 11 students who took the pretest were able to answer with a model that was even marginally close to the accepted physical model. The one that was close did not have a complete physical answer. This is no surprise as this question was administered prior to instruction.

When this same question concerning the frequency change and the photon model of light was asked post instruction, 10 of the 14 students who took the posttest provided an acceptable explanation that discussed the main elements of the physically accepted model. Of the 10 whose explanations were acceptable, 6 were judged to be excellent while 2 more were very good.

Also of interest were student post instruction responses to the question concerning how to modify the light source in the classical model so as to eject electrons. Only 1 of 14 respondents was able to answer this question acceptably. Most students answered the question by suggesting that the frequency be changed as per the photon model of light. It appears these respondents answered as if the question was asking about changing the light source in terms of the quantum rather than classical model.

Tutorial and Laboratory Discourse Analysis and Tutorial Data

As part of the curriculum of the modern physics class, the students were required to use the program *Photoelectric Tutor* to complete the first activity in *A New Model Course in Applied Quantum Physics* tutorials. In this activity, the students worked in groups of two on the Graphing I vs. V section of the *Photoelectric Tutor* program. After completing this section of the program, the students then answered the three questions posed in the tutorials. The first of these questions asked the students to determine the work function for various metals and explain how they did this, the second asked them to predict the stopping voltage and light frequency for sodium and check their answers using the program, while the third question asked them to use the program to determine the value of h/e and explain how they accomplished this.

In a previous study on the effectiveness of *Photoelectric Tutor*[4], students were asked to use the program as a homework assignment outside of class time. Students using the program in that study showed a marked improvement in their understanding of the photoelectric effect as compared with a similar set of students who did not use the program. Our usage of *Photoelectric Tutor* software differed from previously published studies in that we required the students to work on the program and the associated questions in groups of two during lab time.

A by-product of the student usage of the program during laboratory time was a chance to record the students' conversations as they used the program. We were also able to correlate these data with student responses to prompts within the program that were stored by the program. From our preliminary analysis of these data two key points standout:

Use of the photoelectric tutor program by groups in a laboratory setting enhanced the value of the program. By requiring the students to use the program in groups of two, students engaged in significant discourse prompted by the feedback provided by the program. Analysis of the transcripts of student discourse in conjunction with the pre/posttest results suggests that students benefited from their discussions with fellow students. This agrees with the results of other researchers in PER who have seen gains in student learning as students work in cooperative groups on interactive computer programs [5].

Student weaknesses in other subject areas, such as electromagnetism, electric circuits or waves can be obstacles to their understanding of the photoelectric effect and its implications for the photon model of light. As was seen on the pretest, a large percentage of the students had trouble understanding the circuit diagram of the traditional photoelectric effect experiment (see Appendix) and understanding that increasing the intensity of the light was the classical approach to eventually ejecting electrons. Analysis of the student discourse while using the *Photoelectric Tutor* reveals that these weaknesses in related subject areas slow student progress toward completing the tutorial. Though they were not required to do so, 3 of the 6 groups used the electric circuit tutor portion of the program. Transcripts of the discussions from these groups reveal that one group member had serious misconceptions concerning the operation of the circuit. Recordings of the tutorial use and posttest results suggest that many of these problems were overcome during tutorial use and in subsequent instruction.

Discussion

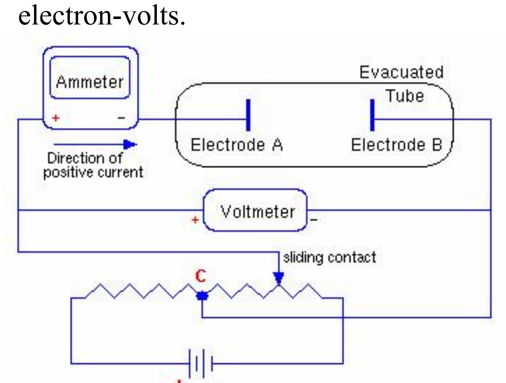
The results to date in this study provide a number of insights into the student learning processes in the photoelectric effect. Probably the most significant result is that the level of student understanding of electromagnetism, electric circuits and waves coming into instruction is important to the student's understanding of the photoelectric effect and its implications for the photon model of light. If a student does not understand that the classical model of light suggests increasing the intensity of the light to deliver more energy to the electrons, and thus eject them from the metal, the student may not grasp the significance of increasing the frequency of the light to accomplish this same task. Moreover, if a student has a difficult time interpreting a circuit diagram, the significance of the I vs. V curve may be lost on the student.

Results also suggest that the program *Photoelectric Tutor* can be successfully used as part of the curriculum in a group environment. The quality of the student discourse as the students used *Photoelectric Tutor* points to the value of having both students convinced of a response prior to answering a prompt. This result is in line with other findings on the value of small group discussions in the classroom.

The results also point to a failure on the part of the students to answer correctly the posttest question concerning modification of the light source in the classical model. A large number of students answered the question on the classical model incorrectly post-instruction. At this stage it is not clear why the student responses to this question were so poor. It may be that ambiguities in the question itself led to these responses. Another possibility is that some students have a difficult time keeping and applying more than one model of a given phenomena.

Appendix

1. Consider the classical model of electromagnetic radiation (light) that you learned in your previous physics classes.
   a) As a single frequency of electromagnetic radiation continually strikes a metal, what should it cause to happen to the metal? Why?
   b) Suppose that you controlled the source of the radiation, and could change it in any way that you wanted. How would you modify the electromagnetic radiation source (light source) such that the radiation, upon striking the metal, would free electrons from the surface? Briefly explain why you think this method would work.
2. Consider the circuit below where electrodes A and B are in a vacuum. Suppose that electrons are continually liberated from the metal that forms electrode B and that the electrons that are liberated have a maximum energy of X electron-volts.



On the axis below make a sketch of the current through the ammeter as function of the voltage as read at the voltmeter.

(Note: Question 3 of exam was administered after questions 1 and 2 were turned in.)

3. It is known that electrons can be freed from metals by increasing the frequency of the light that is striking them, even if the intensity of the light is low. Increasing the intensity of low frequency light has no effect. However, if you have a possible explanation for this phenomena, or can think of one in a few minutes, please share this explanation below.

References

[1]E.F. Redish, R.N. Steinberg, and M.C. Wittman *A New Model Course in Applied Quantum Physics* (Demonstration Version).

[2]Available from Physics Academic Software

[3]PASCO's "h/e System" p. 312 of 2003 PASCO Physics Catalog and Experimental Guide

[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 and R.N. Steinberg, G.E. Oberem, "Research-Based Instructional Software in Modern Physics," JCMST **19** 115-136

[5] Goldberg, F. (1997). Constructing Physics Understanding in a Computer-Supported Learning Environment. In Redish, E.F. and Rigden, J. (Eds.) *The Changing Role of Physics Departments in Modern Universities: Proceedings of the International Conference on Undergraduate Physics Education. Part II: Sample Classes.* American Institute of Physics.