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Measurement and Interpretation of Undergraduate Students' Writing about the Experiments of the Photoelectric Effect

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This study aimed at examining undergraduate students' writing about experiments related to the photoelectric effect and giving some implications for experiment education. Thus, this study analyzed 26 students' reports about three kinds of experiments: measuring Planck's constant, comparing the photocurrent and the photovoltage across the intensity of light, and comparing the photocurrent and the photovoltage across the frequency of light. In the measurements, less than 25% of the students expressed the data to the correct number of significant figures even though two-thirds of the students successfully obtained the data given in the manual. In terms of interpretation, the students were not aware of the physical meanings of the detailed parts in the graphs. Even though over 50% of the students drew a line relating photocurrent to voltage, no students compared the theoretical to the empirical data or made a judgment as to whether of not the background theory really fit the experiment. The research findings showed that insufficient knowledge and skills for physics inquiry may be an obstacle in performing the experiments well.

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Keywords: Photoelectric effect, Scientific inquiry, Experiment report, Physics experiment

I. INTRODUCTION

The demarcation between classical and modern physics was made in the beginning of twentieth century. Planck introduced the action of quanta to solve the limitations of Wien's law and equipartition theorem about the black-body radiation [1,2], and with the concept of quantum, Einstein explained the interesting phenomenon that electrons are released from the metal while specific frequency of light radiates to the metal [3]. The photoelectric effect is crucial in progression in modern physics because it fits for the quantization of light quanta and wave-particle duality of light. The phenomenon was first discovered by Hertz, and Einstein formulated theory of light and his ideas influenced the hypothesis of de Broglie [4]. Nowadays, the photoelectric effect is introduced in many courses for general and modern physics and undergraduate students in physics major do experiments to measure the photocurrent or stopping potential [5–8]. As well, the experiment is used to determine Planck's constant since Einstein first employed Planck's concept to the emission of electrons from the metal [6,9].

The photoelectric effect can be used as a diagnostic tool to figure out students' understanding of quantum mechanics and empirical abilities in relation to inquiry. Students would not be able to understand the threshold frequency of light if they focused on the undulatory nature of light. Conversely, they would fail to understand how the frequency of light affects the electric potential. Besides, they should recognize how energy of photons is transformed into kinetic energy of electron [10]. This indicates that the photoelectric effect is connected with

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wave-particle duality of light, which is crucial in understanding traditional interpretation of quantum mechanics, the Copenhagen interpretation [11,12]. On the other hand, doing experiments about the photoelectric effects entails fundamental actions in physical inquiry. First, student should derive a formula to explain the relation between frequency of light and stopping potential as shown Eq. (1).

$$KE_{max} = eV = h\nu - \varphi \quad (\varphi : \text{work function}) \qquad (1)$$

They should be able to represent graphs with the obtained outcome and compare between experimental and theoretical data. As well, they should figure out influencing parameters such as work function of anode and effect of space charge [13, 14], and propose more elaborate procedures. They should distinguish observation from interpretation during the experiment, and be familiar with mathematical formalism to compare theoretical prediction and experimental results. The analysis of students' reports on the phenomenon is one of the best ways to investigate how students understand the photoelectric effect and the nature of light. Thus, this study aims at investigating the capabilities of undergraduate students for physics inquiry centring on measurement and interpretation, and examining their difficulties in understanding physical concepts related to the experiment.

II. RESEARCH METHODS

In this study, the researchers investigated 26 students attending the undergraduate for doing physical experiments. All of them were sophomore students consisting of 17 male and 9 female students in the department of physics education. The subject titled as "physics experiments and demonstration II" is compulsory for all preservice teachers, and they should enrol the subject after taking lecture-based and experiment-based subjects as follows: general physics I, II, experiment for general physics I, II, teaching for classical mechanics, and physics experiments and demonstration I. In the subject, they were supposed to do a series of experiments related to the photoelectric effect as listed: Planck's constant, I-V with different intensity of light, and I-V with different frequency of light. A set of experiment devices made in Pasco (AP-8209) was used for the experiments. Mercury lamp was used as a light source and the intensity of light was adjusted by the apertures with different diameters (2 mm, 4 mm, 8 mm) and the optical filter was used to adjust the frequency (365.0 nm, 404.7 nm, 435.8 nm, 546.1 nm, 577.0 nm). In experiment 1 to measure and calculate Planck's constant, students were asked to measure the stopping potential while different wavelengths of light radiated on the photodiode. In experiment 2 to measure I-V with different intensity of light, current and voltage were measured under the different apertures (2 mm, 4 mm, 8 mm) and the same wavelength (436 nm). In experiment 3 to measure I-V with different frequencies of light, current and voltage were measured under the different wavelengths (435.8 nm, 546.1 nm, 577.0 nm) and the same aperture (4 mm).

The three experiments they conducted in this study had different emphases. For example, the first experiment related to Planck's constant helps student to calculate the constant and the work function of the used metal through the linear relationship between frequency of light and stopping potential, whereas the second experiment shows that photocurrent depends on the intensity of light through the saturated curve.

In order to examine students' difficulties in the experimentation related to the photoelectric effect, this study concentrated on the measurement and interpretation among their activities. One of overarching goals of experimentation in physics education is to improve the abilities of scientific inquiry [15,16]. Scientific inquiry implies a series of actions to construct scientific knowledge or to solve scientific problems, and the process can be divided into five domains: identifying problem, designing experiments, implementing experiments, interpreting data, and making conclusions [17]. The manual given to the student provided the experimental topics, procedures and the variables to be observed. Students were encouraged to perform the experiments, to keep track of observation results, to transform one into another data, and to interpret the results. Thus, this study concentrated on implementing experiments and interpreting data.

The assessment framework for scientific report was based on the results of Kim and others' study [18]. They suggested evaluation criteria for each element of scientific inquiry. As for the measurement, they presented

Table 1. Evaluation criteria for experimental report in the photoelectric effect.

Domain	Criteria	Explanation
Measurement	Data acquisition	Acquiring all data required in the manual
	Significant digits	Record of appropriate significant figures (*e.g.*, 5.00 V, 5.000 V)
Interpretation	Use of graph	Conversion of data to graph, expression of trend line and formula, error bars, regression results
	Interpretation of graph	Meaning of x-, and y- intercept, slope of graphs, coefficients in trend formula
	Comparison of theory and practice	Comparison between theoretical and experimental data (Planck's constant and work function), and its interpretation
Conclusion	Inference	Making a conclusion from the obtained results

Table 2. Assessment result of students' report on the photoelectric effect.

Domain	Criteria	Planck's constant	I-V under different intensity	I-V under different f
Measurement	Data acquisition	17 (65.4%)	23 (88.5%)	24 (92.3%)
	Significant digits	6 (23.1%)	0 (0.0%)	0 (0.0%)
Interpretation	Use of graph	10 (38.5%)	21 (80.8%)	22 (84.6%)
	Interpretation of graph	6 (23.1%)	13 (50.0%)	8 (30.8%)
	Comparison of theory and practice	1 (3.8%)	0 (0.0%)	0 (0.0%)
Conclusion	Inference	12 (46.2%)	0 (0.0%)	0 (0.0%)

three kinds of criteria as listed: selection of experimental apparatus, record of observation/measurement, and classification of the obtained data. Interpretation is composed of four criteria: use of symbols and diagrams, use and interpretation of graphs, qualitative explanation depending on concepts and principles, and quantitative analysis. Based on those, the study established a few of checkpoints for the better understanding of experimental physics in relation to the photoelectric effect as seen in Table 1. In terms of the measurement, appropriate selection of apparatus did not have to be concerned because the detailed information was already written in the manual. Instead, this study checked out if the students kept record of all data required in the manual. In relation to the classification of data, this study took into account whether the students could record the data following the significant numbers. In respect to the interpretation, this study reflected depiction of various information on the graphs such as trend line, error bars and regression results, and understanding of the signs and symbols on the diagrams. For example, students should be able to draw a 2D plot with the measured data (frequency and stopping potential) in the experiment 1. As well, they should recognize the meaning of x-intercept (threshold frequency), y-intercept (work function over electric charge), and the slope (Planck constant over electric charge). Once a background theory is adopted, the obtained data is used to examine whether the experiment fits theoretical arguments. If any errors are found according to the comparison, the experimental design is modified and the experiments are done iteratively. In this reason, this study thought highly of comparison between theory and experiment and appropriate error analysis. The qualitative analysis in the interpretation was substituted for inference to make conclusions. The main goal of experiment is to build up an argument and in the educational context, the argument is linked to conceptual understanding of physics. This study examined if the report explicitly articulates conclusions based on the experimental results in an appropriate way. The reports about the three experiments in the study followed aforementioned criteria and the results are shown in Table 2.

III. RESULTS

1. Experiment for Planck's constant

This experiment was to measure the stopping potential to refrain the photovoltage evoked by photons according

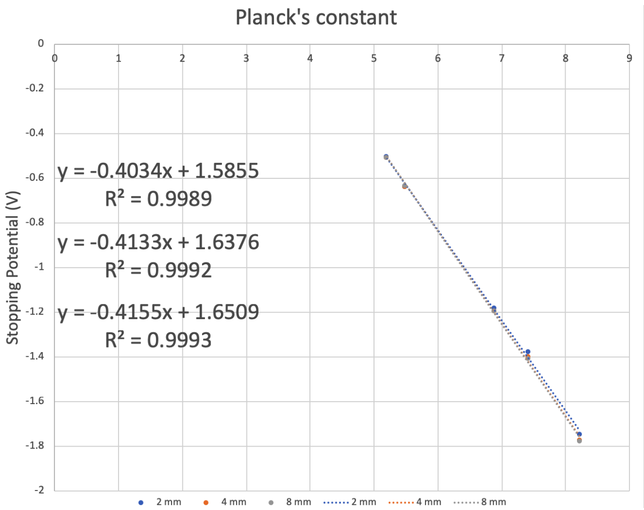

Fig. 1. (Color online) The example of students' diagram showing the relation between frequency of light and the stopping potential.

to the different frequency and intensity of light. They were asked to measure the stopping potential evoked by five different frequencies (365.0 nm, 404.7 nm, 435.8 nm, 546.1 nm, 577.0 nm) and three different intensities. The intensity of light is differentiated by adjusting the cross-sectional area of light projected on the metal with different radii (2.0 mm, 4.0 mm, 8.0 mm).

In regard to the measurement, 17 out of 26 students examined all the experiments given to them. Measurement of frequency and voltage across the different conditions is very important because the main objective of this experiment is to obtain the linear relation between frequency and the potential denoted as h/e regardless with frequency and intensity of light. If they do not measure according to the different intensity of light, they will not be aware that the intensity is not influential to the relation. Problematic was that only 6 students kept track of measurement results following the rule of significant figures. This indicates that most of students just wrote down the numbers seen on the screen of devices, and more problematic is problematic that they might not think over the accuracy of the experiment and the error analysis. No student did the experiments repetitively but did only one time. Neither did they consider the error analysis nor express the deviation of data.

In terms of interpretation, we examined how well students performed the expression of data with graphs and meanings of graphs. As a result, fifteen students who recorded the stopping potential wrongfully drew a graph with minus slope. Twenty-four students out 26 students expressed the trend line and formula and 22 explained the meaning of slop in the graph. However, over half of students (15) plotted a straight line with the decreasing slope (see Fig. 1). This is problematic because the stopping potential is reversely exerted on the circuit to cancel out the photovoltage. Thus, the signs need to be converted into the plus signs. Otherwise, the relation v and V would be inversely linear. It is likely that they did not distinguish the stopping potential from the photovoltage. Even though 22 students obtained Planck's constant from the slope, only 6 students derived work function from the results appropriately. Even some of students misunderstood that the y-intercept in the graph stands for the work function. In fact, the work function is a value of y-intercept divided by e (1.6×10^{-19} C). Regarding the comparison between theoretical and experimental results, most of students only considered Planck's constant but not work function. It is true that the outcomes of the experiment can be applied to derive Planck's constant but more important in this experiment is to understand the wave-particle duality of light, and work function is often suggested as an example to falsify the undulatory nature of light. Despite they mentioned about Einstein's photon theory, they did not care about work function or guess what metal was used in the experiment (Fig. 2). Even, they did not induce the threshold frequency which can be obtained from x-intercept of the line. The mean value of work function obtained from the experiment is 1.6 eV but the deviation between theoretical (2.29 eV for potassium) and experimental data is huge, while the error percentage of Planck's constant was under 5 %. This indicates that other conditions affect the results such as the distribution of electric field exerting on the cathode and anode, polarity of light, and effect of space charge.

While making conclusions, less than half of students (12) mentioned that the slope is consistent with the intensity of light. It is natural because only 17 students succeeded in obtaining all the data and even 15 students failed to draw a line of relation between frequency and potential. Although making conclusion is more important than any other process in inquiry, students tended to do the experiment as making food just following the

1905년 Albert Einstein은 Planck의 이론을 이용하여 간단하게 설명했다. 새로운 양자 기본 모델은 높은 진동수의 빛이 높은 에너지를 가진 전자(광전자)를 방출하며, 빛의 세기가 증가하는 것은 방출된 전자의 개수(광전류)를 증가시킬 뿐 전자를 방출하는 여부와는 관계가 없다는 것을 설명할 수 있었다. 만약 전자가 금속표면 아래에 있다면, 표면 위로 이동하기위해 에너지를 흡수할 것이다. 이것을 일반적으로 '일함수(W_0)'라고 한다. 만약 양자의 에너지가 일함수보다 크다면, 전자는 특정한 양의 운동에너지를 가지고 방출된다. Einstein은 Planck의 이론을 사용하였고, $E = h\nu = KE_{max} + W_0$ 를 사용하여 광전효과를 사용했다. 여기서 KE_{max}는 방출된 광전자의 최대 운동에너지이다. 여기서 운동에너지는 $KE_{max} = h\nu - W_0$ 로 쓸 수 있다.

만약 수집판이 정지전위를 가지도록 음극으로 대전되었다면 방출된 전자는 수집판에 도달할 수 없고, 광전류는 0일 것이다. 가장 높은 운동에너지를 가진 전자는 eV의 에너지를 가질 것이며, 여기서 e는 전자의 전하량이고 V는 정지전위이다.

$$eV = h\nu - W_0$$

$$V = \frac{h}{e}\nu - \frac{W_0}{e}$$

In 1905, Albert Einstein explained [the experimental results] simply using Planck's theory. The new quantum model explained that photons with high frequency allowed to emit (photo)electrons from the metal and that the increasing intensity of light engaged only the quantity of electrons (the photocurrent) but not relevant to threshold of emission of electrons. If electrons are placed under the surface of the metal, they should absorb energy to go out from the metal. This is work function denoted as W_0. If energy of photons is bigger than the work function, electrons will be escaped from the metal. Einstein applied Planck's [quantum] theory and explained the photoelectric effect with the formula $E = h\nu = KE_{max} + W_0$, where KE_{max} is maximal kinetic energy of photoelectrons. The formula can be expressed as $KE_{max} = h\nu - W_0$.
If the plate receiving electrons are negatively charged to have the stopping potential, the emitted electrons cannot reach the plate and the photocurrent will be zero. The maximum energy of electrons is eV where e is quantity of charge of an electron and V is the stopping potential.

$$eV = h\nu - W_0$$
$$V = \frac{h}{e}\nu - \frac{W_0}{e}$$

Fig. 2. An excerpt from students' report and the translated text.

recipe. This result addressed that doing experiment carelessly may impede their understanding of physics unless they understand the objective of experiment and keep the appropriate process of inquiry.

After all, the students did not seem to have enough capabilities with physics inquiry. Even though the manual given to them articulated what data should be obtained explicitly, 9 out 26 students failed to satisfy the measurement according to the different intensity of light, and six students considered the significant figures appropriately. Even more, no student took into account statistical or experimental errors on doing experiment. The inappropriate expression of the graph caused a series of mistakes calculating Planck's constant and work function. What if they measured all data required and plotted them well, they would figure out the same slope in the diagram and reach the right conclusion. The comparison between theory and experiment was seldom done according to the reports. If then, they would find out the reasons about the deviation of errors and improve the experiment. However, most of students did not make clear argument from the results. As well, it is important for students to understand the objective and the meaning of the experiment clearly. Although the equation to explain the relation between frequency of light and stopping potential was given to the students, they miscalculated the key variables without division of the values by e. Even, they did not much care about work function and threshold frequency. The experiment shows the nature of light quanta as wave-particle duality but if they only focus on quantized energy of photons, they will miss the undulatory nature of light. This is because the work function is determined by the frequency of light and frequency is the character of undulatory entity [19].

2. Experiment for I-V in the context of different intensity of light

The objective of this experiment is to measure the photocurrent and the photovoltage and examine the relation according to the different intensity of light. The intensity of light was adjusted by the radius of aperture from the light source (2 mm, 4 mm, 8 mm). That is to say, the intensity of light is proportional to the square of radius. The assessment result of measurement in this experiment was similar to the case of the first one. 23 out of 26 students satisfied measuring I and V according to the different apertures but no students succeeded in expressing the data satisfying the rule of significant digits (partial satisfaction was 14 students). Neither did anyone consider the error analysis.

In respect to the interpretation, we examined whether the students performed drawing graphs and understood the meaning of graphs well. According to Eq. (1), the photovoltage depends on the frequency and the curves formed by three different intensities of light will have the same stopping potential (x-intercept). However, the intensity of light emanating from the light source caused more emission of photoelectrons and affects the photocurrent. That is to say, the photocurrent is increasing but saturated to the specific maximum point which relies on the intensity of light. As a result, 21 students transformed the data into the graph successfully but no one derived the trend line and equation to explain the relation between I and V. Even, there was no experimental result showing the saturation of the photocurrent. In fact, derivation of the equation needs understanding of modern physics. According to the classical electrodynamics, electric force acting on the photoelectron is $F = qE = eV/l$ (l: distance between anode and cathode). The work of electron by electric force is equal to the change of kinetic energy $\left(\frac{1}{2}mv^2 - \frac{1}{2}mv_0^2\right)$, and it is denoted as follows:

$$\int_x^0 eV/l ds = \frac{1}{2}mv^2 - \frac{1}{2}mv_0^2 \quad (x: \text{distance from the initial position}) \qquad (2)$$

Hence, the velocity can be expressed as $v = \sqrt{v_0^2 + \frac{2eV}{m}}$, and when we consider Eq. (1) and current density, the photocurrent is denoted as $I = I_0\sqrt{1 \pm \frac{eV}{hv - W}}$ [20]. However, in modern physics, an electron is a fermion and while considering Dirac-Fermi distribution, the probability of a particle with energy E is $f(E) = \frac{1}{1 + \frac{\exp(E - E_f)}{kT}}$ (E_f: Fermi energy). Regarding KE_{max} of a photoelectron, the intensity of the photocurrent is depicted as follows:

$$I(V) = \frac{I_{max}}{1 + \exp((V - V_c)/V_0)} \quad (V_0 = kT/e\ , \quad V_c = \delta + \varphi – (h/e)v) \text{ [21]} \qquad (3)$$

Eq. (2), which is based on classical electromagnetism, is only satisfied with the condition where the photovoltage is enough high at a very short period [22]. A couple of students stated that the photocurrent is increased logarithmically. However, the current is quasi-exponentially increasing at first, then is increasing like square-root shape shown in Eq. (2).

While interpreting the graph, half of students were aware that x-intercept points to the stopping potential. On the contrary, only 8 students tried to examine whether the maximum photocurrent is really proportional to the square of the radius. As long as the photocurrent does not reach the maximum value, the relation cannot be verified. After all, due to the insufficient data and tumbling on the derivation of the equation, all of the students did not have the expected outcome and conclusion. Fig. 3 shows the relation between photocurrent (y-axis) and photovoltage (x-axis) across different intensity of light. Despite a couple of students dare to say that they could find out the saturation value of the photocurrent, it is unclear that the photocurrent approaches the maximum value.

The analysis of students' reports about the second experiment also revealed the students did not obtain enough data to make conclusion. Since they failed to derive an equation to relate the photocurrent and photovoltage, they could not compare their results to the theoretical ones. The results of the second experiment also turned out that it is necessary to acquire fundamental knowledge and skills for physics inquiry and to understand the goal of experiment.

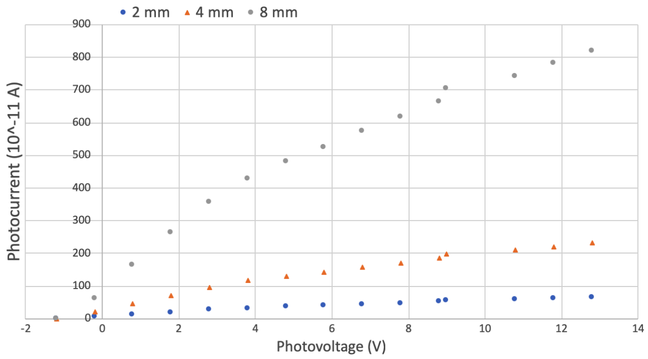

Fig. 3. (Color online) An example of I-V curves according to the different intensity of light.

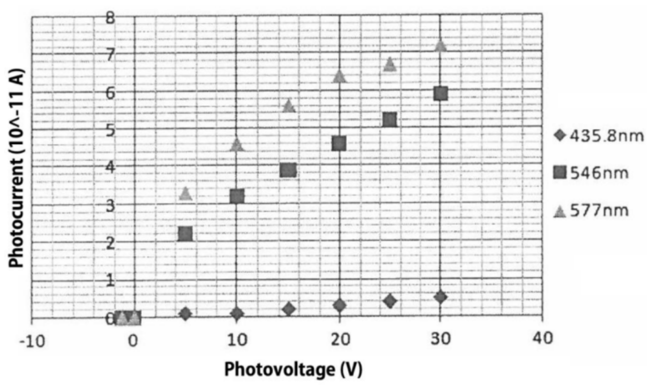

Fig. 4. A student's example of I-V graph according to different frequency of light.

3. Experiment for I-V in the context of different frequency of light

This experiment intends to examine the photocurrent and photovoltage under the different wavelength (or frequency) of light. It is expected to have different voltages but the similar maximum current across the different frequencies. While assessing the measurement, we focused on the measurement of all data required and the expression of significant figures. Twent-four students satisfied measuring data required in the manual whereas no one kept track of the data following the expression of significant figures. The result was very similar to that in the second experiment.

Similar to the second experiment, the students mostly successfully drew a graph from the obtained data but could not derive an equation or consider error analysis. The equation derived in the second experiment (Eq. (3)) can be applied here. If they understood the role of frequency in the photoelectric effect, they could figure out that the three different curves have different x-intercepts, which indicates the threshold frequency. Only 8 students were aware of the difference of x-intercepts about the three graphs, and caught up the meaning. As shown in Fig. 4, most of students did not examine whether the stopping potentials according to the different frequency of incident light are differed. Neither they did compare theoretical and experimental data nor make a successful conclusion from their measurement results.

As a consequence, basic knowledge and skills for physics inquiry was crucial in doing experiments, similar to the results of the second experiment. Although the students measured the current and voltage well, they did not know what to see. Even, they failed to build up an equation to explain the results and could not compare theory and experiment. Moreover, they could not propose any suggestion for more accurate results. Despite the significance of the frequency of incident light on the photoelectric effect, no students successfully conducted this experiment.

IV. DISCUSSIONS AND IMPLICATIONS

This study analysed students' experiment reports about the photoelectric effect with a focus on the measurement and interpretation, and examined their understanding of physical concepts in relation to the photoelectric effect. In this study, we analysed the experiment reports written by 26 undergraduate students enrolling physics experiments and demonstration, and their reports were comprised of three different experiments: the relation between the frequency and the potential, the relation between I and V according to the intensity of light, and the relation between I and V according to the frequency of incident light. The assessment of their reports followed the criteria presented in Table 1, and Table 2 shows the summary of the whole results about the assessment. The numbers in the table implies how many students performed the given actions appropriately. Here, we ruled out the students who satisfied the criteria partially.

The results of this study disclose several problems related to experimental activities. First, the basic knowledge and skills for inquiry is prerequisite for the performance in physics inquiry. Albeit the manual for the experiments were given to the students, some of them could not finish gathering all the data required in the manual and no one could successfully treat the data such as the significant figures and error analysis. While interpreting data, some of them converted the data into the graph appropriately, and many of the students were not aware of the meanings of symbols and signs provided on the graph. In the second and the third experiments, no student made an appropriate argument for the results. Moreover, many of them neglected important information such as work function and the stopping potential in the first experiment. This indicates that the students should be able to understand the objectives and values of physics experiments.

Second, conceptual understanding and mathematical formalism are crucial in doing physics inquiry. The photoelectric effect is based on Einstein's quantum theory of light and the experiments in the study are connected to Eq. (1). In particular, the students should be able to understand the contents of modern physics to derive Eq. (3) from the data. The equation is based on Fermi energy in the particle physics unlike electric force acting on an electron. And, they should be able to recognize what ought to be observed in the experiment. For example, the maximum current was measured after saturation, but most of students missed the fact.

Third, the conceptual understanding is closely linked to the recognition of the objectives and values of physics experiment. In this study, the main purpose of the experiment was to measure Planck's constant. However, the constant was derived from the mathematical extrapolation to solve the black cavity radiation, and Einstein tried to explain the photoelectric effect using the concept of quantum and his results well matched Planck's assumption. As a consequence, Einstein came to think about the dualism of light. For such reasons, the experiment encompasses many parameters as work function, maximal kinetic energy and threshold frequency connected to both corpuscular and undulatory nature of light. Conversely, de Broglie brought his idea and applied it to the matter (wave-like form of matter) and this idea supported the wave-particle duality and uncertainty principle. We need to provide students with more opportunities to discuss the expression of formula and semantics of various information shown in the diagrams for the better understanding of related physics.

The research finding which showed serious problems in doing physics experiment may implicate for developing a guideline for physics inquiry. Even though the recent revised curriculum stresses scientific inquiry [23], student should have more opportunities to find out the problems and to do the experiment iteratively to reach the appropriate conclusion. The cook-book style manual is helpful to lead the right answer which is consistent with what they learned. However, such an easy way may deprive of a chance to make their own questions and to fix up their faults. To enhance their abilities for physics inquiry, there should be an elaborate framework for assessing the physics experiment report and it will be helpful to find out what process should be more improved from identification of the problems to the establishment of conclusion. Further, the experimentation in physics should include not only empirical guidelines but also historical and philosophical aspects of physics. This study will be a starting point to renovate experiment education in physics.

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