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Investigation of the Profiles of High School Students' Mental Models of the Concept of Photoelectric Effects

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A mental model was students' internal representation when they learned a concept. The conceptual model is a description of natural phenomena following the views of scientists. Most high school students have an idea of classical physics on understanding the concept of the photoelectric effects. Understanding the photoelectric effect is key to comprehend the fundamentals of quantum physics. The photoelectric effects can explain the quantization of energy that is explainable by a classical physics theory. This research's learning modeling aims to identify and investigate the profile of Class XII high school students' mental models by regarding the concept of the photoelectric effects. This research employed descriptive methods. The research sample was selected purposively. This research used a diagnostic test for the pretest to determine the initial knowledge about the photoelectric effect of 30 students (12 male students and 18 female students) from the XII MIPA class at SMA Negeri 1 Pekalongan. The pretest questions consisted of 4 description questions. The pretest results were then analyzed and used to determine six students for an interview process, two students with high results, two students with medium results, and two students with low results. The interview results reveal that the students usually implement classical physics knowledge when developing mental models of the photoelectric effects.

1. Introduction

Physics learning as a part of natural sciences are divided into three representation levels: the macroscopic, microscopic, and symbolic levels (Pratiwi et al., 2018; Priyadi et al., 2019). Macroscopic representation is a way of comprehending physics through occurring phenomena in daily life (Handayanti et al., 2015). Microscopic representation is a way of comprehending physics through the particles' interaction that creates objects to explain physics concepts (Knight, 2017; Kurnaz & Emen, 2014). Meanwhile, symbolic representation is a way of comprehending physics through symbols and physical units formulated into mathematical equations (Amrizaldi et al., 2014). The comprehension of the three representation levels is called the mental model (Wahid et al., 2016).

A mental model is a student's representation of an idea whose results are obtained during the cognitive process when a teaching-learning process is completed (Arianti & Yuliati, 2018). The mental model is also considered to represent ideas in a person's mind to describe and explain phenomena (Yoni et al., 2019). This model is created from continuous interaction between the mind and nature to produce understanding through an internal interpretation process (Edward-

Leis, 2015; Kurnaz & Eksi, 2015). Mental models in physics learning describe a system and its components related to a change in condition to another (Siswoyo, 2015). Lutfia et al. (2020) researched mental models and explained that a mental model enabled teachers to discover students' understandings expressed indifferent ideas when explaining a phenomenon. Understanding the three levels of physics representation reduces the occurrence of alternative conceptions; thus, students' knowledge of physics becomes comprehensive (Griffith et al., 2018).

Classification of students' mental models of quantum physics material is classified into realistic, quantum, and agnostic (Hermawan et al., 2015). Meanwhile, Ireson (2000) classified mental models into several clusters: entities, mechanics, quantum, and thought conflicts. Students' mental models for studying the photoelectric effect concepts were identified as particle-wave models, light models, and particle models (Gercek & Oszan, 2015). Some quantum phenomena are counterintuitive concepts for everyday thinking and reasoning in classical mechanics. Therefore, it is necessary to understand quantum theory using non-classical interpretations (Mulyati et al., 2018). Teaching quantum physics to high school students must know the construction of their mental models (Wahid et al., 2016).

A preliminary study on class XII students of SMA Negeri 1 Pekalongan reveals several differences in the level of students' mental models in visualizing the process of the photoelectric effects. Five groups of students visualized the photoelectric effects by combining the wave-particle model (hybrid model). Meanwhile, seven groups of students visualized the photoelectric effects as a beam-ray model. Three groups of students visualized the photoelectric effect as a particle model. These differences indicate that the students have different understandings of the concept of the photoelectric effects.

An investigation of the students' mastery of the materials tested in the 2019 national high school examination denotes that the students' mastery of modern physics material is 48.20%. This result is the lowest percentage among other physics materials, such as mechanics, waves and optics, thermodynamics, electricity, and magnetism. At the national level, the percentage of students with correct answers for indicators explaining physical quantities related to the photoelectric effects was only 53.63% (Puspendik, 2019). Four major factors influence this result. The first factor is the high school students' misconception in which they assume that if the light frequency increases, the light intensity will increase. The second factor is a light intensity effect on the photoelectric effect occurring when the light frequency is less than the metal threshold frequency. The third factor is the students' assumption about the stopping potential is equal to the amount of emerging light energy. The fourth factor is the students' frequent statement that if the photons’ energy is less than the metal work function, the light’s intensity must be increased to release electrons successfully.

The mental model theory that underlies the instruction of the learning modeling method in physics tries to organize several basic models into basic patterns (Amalia et al., 2018). Misconceptions usually occur in basic models and are in the form of a wrong understanding of previously studied concepts (Olsen, 2002). Based on the problems described, this study investigates the profile of students' mental models of the photoelectric effects on understanding the conceptual and graphic relationship among intensity, incident ray frequency, and potential differences. Therefore, the students' mental models on the photoelectric effect materials necessarily help teachers implement appropriate learning strategies that enable students to understand the conceptual models. This research expands the results of this research to determine the profile of research by Gunawan et al. (2014).

Furthermore, this research aims to determine the profile of students' understanding of modern physics concepts, and thus, the teacher conducts direct interviews related to the students’ concept of photoelectric effects. In addition to interviews, this research employed a diagnostic test consisting of essay questions whose answers must be accompanied by a picture related to the concept of the photoelectric effects. Whereas previous research by Gunawan only focused on investigating strategies to improve students’ generic skills by applying a modern physics virtual laboratory model (Gunawan et al., 2014). This method is expected to develop analogy, modeling, and modeling skills as the main characteristics of theoretical formation in science; learning physics using the modeling method builds relationships between theory and natural phenomena (Yildiz & Buyukkasap, 2011).

2. Method

This research employed a descriptive method. Sukmadinata (2007) suggests that descriptive research does not provide treatment, manipulation, or alteration of independent variables, but it describes a condition as it is. Descriptive research is intended to describe a situation or phenomenon as it is. The descriptive method in this research aimed to investigate the profile of high school students’ mental models about the photoelectric effect materials.

The research sample was selected purposively. The implementation of a purposive sampling method allowed an in-depth study of an information-rich situation. The research survey involved 30 students (12 male students and 18 female students) from the XII class MIPA at SMA Negeri 1 Pekalongan. They had studied the photoelectric effect material in semester 2 in the academic year 2018/2019. The students were involved in determining their mental model profiles in understanding the effects of photoelectricity conceptually and graphically.

The instruments of this research were diagnostic tests, interview guides, and documentation studies. The test was in the form of a diagnostic test to investigate the profile of students' mental models of the photoelectric effect material. Meanwhile, the diagnostic test investigating the mental model research was in the form of a Paper-Pencil Questions test (PPQ - test). This test consisted of several questions whose answers were completed with pictures and explanations of the pictures. The compiled questions' difficulty levels were adjusted to the physics syllabus's basic competencies based on the revised 2013 curriculum for class XII in an even semester. Four open-ended questions were selected for the diagnostic test. The students completed the PPQ-test under supervision for 30 minutes. The description of students' understanding of the photoelectric effect materials in terms of the light model analysis and the light model description is limited to the predetermined learning indicators presented in Table 1.

Table 1. Conformity of basic competencies in the revised 2013 curriculum of physics syllabus with indicators of diagnostic test items

Basic Competencies	Question Item Indicators
The 3.8 basic competence qualitatively analyzed quantum phenomena, including the nature of black body radiation, photoelectric effect, Compton effects, and X-rays in daily life.	Describing the characteristics of the wave-particle duality of light Explaining the photoelectric effects Describing the terms and conditions for the photoelectric effects Describingaprocess scheme for the photoelectric effects by using light propagation between a metal surface and a light source

An interview guideline is a list of planned questions delivered to the students (Wang & Barrow, 2011). Selected interviews with a structured model were conducted with students to obtain supporting information and confirm their answers to the diagnostic test of photoelectric effects. In addition, structured interviews were conducted with physics teachers to obtain information and responses to the students' mental models while learning the photoelectric effect material.

The documentation research was employed as guidance to examine the teachers' documentation composed during classroom learning by analyzing the lesson plan of the photolytic effects. The lesson plan was analyzed by creating a transcript and interpreting it to support the obtained diagnostic test results. The test results were categorized based on mental models by Özcan (2015), namely the hybrid model (HM), the scattering model (BrM/ beam-ray model), and the particle model (PM).

The results of the diagnostic test were analyzed by grouping the students with similar answers. The answer groups were categorized, then the percentage was calculated in each category. The students' percentage values, including their understanding of each representation level of mental models, were descriptively interpreted.

3. Result and Discussion

Learning in modeling instructions a construction of mental models representing students' initial knowledge in the form of procedural, declarative, and experimental knowledge (Wang & Barrow, 2011). The knowledge constructed by modern physics is different from classical physics. Knowledge in modern physics is based on derived experience, one of which is constructing a new concept of modern physics derived from the concept of classical mechanical physics with different definitions or special meanings. The meaning of daily classical physics concepts is implemented to explain modern physical phenomena whose explanation is frequently incorrect (Priyadi et al., 2018).

The students' mental model profile of the photoelectric effect concept describes how a general image relates to students' understanding of the concept. The first stage of implementing this mental model was conducting a pretest. The pretest aimed to determine the initial knowledge of 30 students (12 male and 18 female students) from class XII MIPA at SMA Negeri 1 Kota Pekalongan and to discover their initial knowledge of the photoelectric effects. This research used pretest questions in the form of four descriptive questions. Each descriptive question consisted of four questions. Then, each item was analyzed. The results of the question analysis are presented in Table 2.

Table 2. Pretest instrument analysis

Question Number	The number of students with answers	The number of students with nearly correct answers	The number of students with incorrect answers
1	10	12	8
2	12	15	3
3	8	16	6
4	13	17	0

The researchers analyzed four questions that determined the students' understanding of the concept of photoelectric effects. The four questions are:

1. What are the characteristics of the light? Explain your answer by presenting pictures!

Several students answered this question by mentioning that the characteristics of light were both waves and particles. Table 4 shows that eight students answered this question wrongly. Question number two is the first highest question with incorrect answers.

2. What is the meaning of the photoelectric effect?

One of the students answered that a photoelectric effect is an event occurring when a surface, namely a metal surface illuminated by a light packet called a photon. Then the metal surface ejected electrons. Meanwhile, only three students answered this question incorrectly. The majority of them had nearly correct answers about the photoelectric effects.

3. Explain this phenomenon with pictures using light propagation between a metal surface and a light source!

This third question is the second-highest question with incorrect answers. One of the students' answers about the propagation of light between a metal surface and a light source explains that when light shines on a metal with a greater or equal frequency to the metal threshold frequency, electrons will escape from the metal surface with $E_k = h\Delta f = h(f - f_0)$. In the photoelectric effects, light behaves like particles moving like waves.

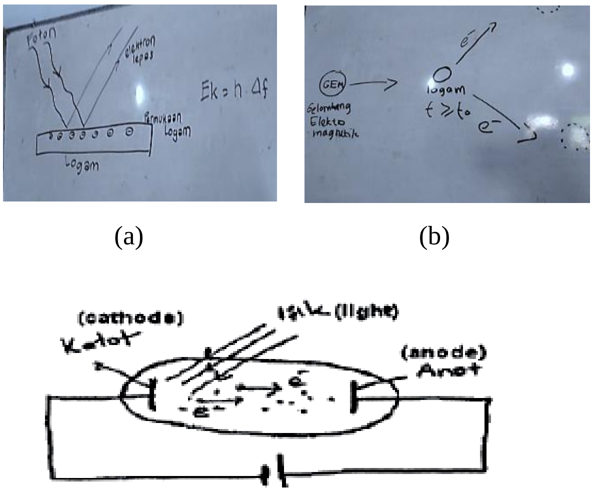
4. What are the terms and conditions for electrons to escape from a metal?

This fourth question has the least error rates because none of the students answered this question incorrectly. In other words, nearly 30 students understand the concept of electrons' conditions to escape from metals. One of the students answered that the photons' frequency must have been greater than that of metals. The wavelength of photons was smaller than that of metals, and the kinetic energy of photons was greater than that of metals. This research determined six students to interview by considering the pretest results. Furthermore, the selected students have high, medium, and lowest pretest scores. The data analysis results create a schema to analyze the students' mental models of light and describe the light model in the photoelectric effects presented in Table 3.

Table 3. Analysis of mental models of light and description of light models in the photoelectric effects

Light models	Descriptions of light models in the photoelectric effect
The hybrid model (HM) incorporating in a wave-particle model	Light (a) is a package, (b) is a transverse wave motion, in which the motion distribution is in the form of particles, and (c) consists of photons (particles) whose trajectory maps are transverse waves.
Scattering model (BrM / beam-ray model)	The light must travel out of the luminous object like a thin beam. The light must travel outward from a luminous object, such as a continuous sine with the same rays' properties.
Particle model (PM)	The light must travel out of objects, such as particles. The light or sine wave is a stream of particles.

The quantum model on the concept of the photoelectric effect asserts that light hitting a metal surface releases electrons from the surface and free electrons. The students were asked to explain the phenomenon with pictures and use light propagation between metal surfaces and light sources. Six students answered the questions about the photoelectric effects with pictures supported by explanations. This research employed three different models selected from the students' drawings, as presented in Figure 1.



(a) (b)

(c)

Figure 1. Students' descriptive diagram to determine radiation models of photoelectrical effects:
(a) Hybrid Model (HM), (b) Beam-Ray Model (BrM), and (c) Particle Model (PM)

The model description in Table 3 reveals that the students try to explain the photoelectric effects using two different models. The models presented in Figure 1 are the wave-particle model (hybrid model), the wave model (beam-ray model), and the particle model (particle model). The data of the three photoelectric effect models show that the students frequently apply the hybrid model. Their mental model is presented in a pie chart in Figure 2.

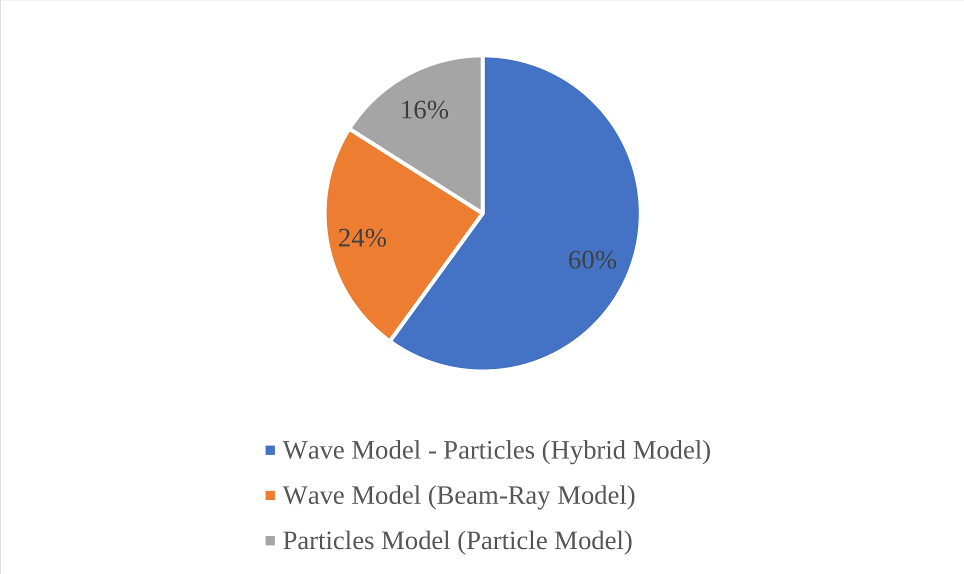


Figure 2. Students' mental models to explain the photo effect materials

Figure 2 shows that 60% of the students prefer the wave-particle model (hybrid model) to explain the photoelectric effects, 24% prefer the beam-ray model, and 16% prefer the particle model (particle model). The students' alternative conceptions were determined by concerning their explanation of the photoelectric effects based on Figure 1. Furthermore, the students widely applied alternative concepts of the wave-particle model (hybrid model) to describe the behavior of light between a light source and a metal surface as a sine wave of particles. These conceptions are summarized as follows:

a. Light behaves like a wave until it hits a metal surface. However, light behaves as a particle during its interactions with metals, indicating that light consists of particles moving like waves.
b. Light consists of photons that create waves at a specific frequency when the waves strike a metal surface.
c. According to the photoelectric effect concept, light behaves like particles whose energy is carried by waves.
d. Photons transfer energy to electrons by absorption. During this transfer, the photons act like packets of waves.

The student who chose the beam-ray model in Figure 1 (b) argued that light traveled as a straight line or a continuous sine wave. The alternative concept of students' using the emitted wave model states that photons transfer energy to electrons. As a result, the waves increase in length. This wavelength change indicates that the photons move as a sine wave. This condition indicates that the light behaves like a wave because there is a change in the photon's wavelength.

The students’ alternative conceptions using the particle model to explain the photoelectric effect explains that electromagnetic waves are packets of energy that hit the metal surface. Then the electrons on the metal surface (cathode) vibrate due to the transfer of energy from these electromagnetic waves, and free electrons with certain kinetic energy occur. After light hits a metal surface, some of the light is reflected while another part removes electrons from the metal. The light scatters as a continuous sine wave; some is absorbed, and some are reflected from the metal.

One of the interviewees asserted that the photoelectric effect occurred when metal was exposed to light, and the electrons came out. Such a light beam is called radiation. Then the teacher asked about radiation. The student answered that radiation was something shining on the metal. Therefore, electrons can escape from the metal.

Another proof of students' appropriate answers to the quantum model is their explanation of any possible effects of the photoelectric effect’s intensity. Some of the students answered that the intensity only affected many electrons to leave the metal. In contrast, the light frequency greater than the metal frequency influences the release or absence of electrons from metals. Consequently, the wavelength of light is smaller than that of metal, and light energy is greater than the energy of metal. When the teacher asked the students to describe the equation of the energy emitted from the metal threshold, they explained that energy from the light emitted and the electrons’ kinetic energy released. This result signifies that the students could decipher the question according to the quantum model. The results of the decomposition of the equation are as follows:

Metal threshold energy $E = hf_0$

$$E = h\frac{c}{\lambda_0}$$

Light energy $E = h\frac{c}{\lambda}$

Kinetic energy $E_k = E_{light} - E_{metal}$

$$E_k = h\Delta f$$

$$E_k = h(f - f_0)$$

This postulate explains several reasons for the need for threshold energy in the photoelectric effect. Furthermore, it explains that an electron's kinetic energy is proportional to the frequency of the light applied, not its intensity. The photoelectric effect and light intensity concepts do not affect the magnitude of the electron kinetic energy. This statement contradicts the view of classical physics that light energy is proportional to intensity. Einstein defined light intensity as each photon's energy multiplied by the number of photons that penetrate one unit of surface-perpendicular area to each unit of time (Aestetika, 2018). Light intensity shows the size of the photon count. The increase in light intensity indicates an increase in the number of photons hitting the metal surface; consequently, the higher the light intensity is, the greater the photoelectric is currently produced (Habibbulloh & Jatmiko, 2017).

Teaching students to construct mental models in quantum physics is different from teaching them to comprehend classical physics. Two items that distinguish quantum theory from classical theory are quantization and uncertainty in measurement results (Yildiz & Buyukkasap, 2011). Quantization is discrete thinking about a continuous item (Amalia et al., 2018). Einstein proposes that classical physics creates the light to be a wave that consists of a discrete collection of photon particles. The quantization of a field means discrete energies limit the vibrations of a field; when interacting with the screen, the field's energy is lost and deposited at the point of interaction (Mulyati et al., 2018).

These final findings show that high school teachers should be more concerned about certain concepts when teaching photoelectric effect materials. First, the light's intensity fired on an experimental plate's photoelectric effect does not affect the size of the electron kinetic energy and the waves' length. Still, it results to a large extent at least. Second, electrons are detached from the metal surface. The teacher must use some concept maps or work frames so that students can connect the concepts.

Moreover, the students should have an opportunity to solve the problem and develop their mental models in the classroom (Purnamasari et al., 2018). This emphasis should be delivered in a learning process or a textbook, and thus, the students can form coherent relationships and organize their knowledge. In fact, each individual has a mental model of the concepts that will develop complex knowledge management about the photoelectric effects.

4. Conclusion

The results of data processing, research findings, and the discussion of the high school students’ mental model profiles of the photoelectric effect material show that most students are categorized to the synthetic level. Besides, they show different understandings of microscopic dimensions. This research reveals the students’ three different descriptions of the photoelectric effect processes: the wave-particle model (hybrid model), the wave model (beam-ray model), and the particle model (particle model). Moreover, most of the students selected the wave-particle model (hybrid model) because they simultaneously used scientific knowledge and non-scientific knowledge. Therefore, they could not use the particle and wave characteristics of light appropriately. The students' different understanding indicates that some of them completely understand the photoelectric effect concept. These diverse understandings can lead to incorrect interpretations when the students visualize a photoelectric effect phenomenon. Future research is expected to illustrate any possible causes of students’ different understanding and explore appropriate learning models required to improve their mental models.

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