A Study of the Nature of Students' Models of Microscopic Processes in the Context of Modern Physics Experiments

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ABSTRACT

University students in modern physics classes were interviewed on their understanding of three fundamental experiments, in order to gain information on their development of models of microscopic processes. In addition, interactive demonstrations were used as a research tool to probe student understanding of modern physics experiments in two high school physics classes. The nature of the students' models and the type of information that they used in order to build a model, both before and after instruction, were analyzed.

I. INTRODUCTION

Research indicates[1] that when the development of models of microscopic processes is introduced as an integral part of a study of electricity and magnetism (E&M)[2], that students are better able to internalize the concepts, build coherent mental models and use those models to analyze and explain physical phenomena. It was found that students who were taught with an emphasis on models of microscopic processes were able to give better explanations on the topic of transients in DC electric circuits in a variety of situations, including those less familiar to them. Students who had not developed models of microscopic processes had great difficulty giving qualitative explanations of macroscopic observations.

While an emphasis on models of microscopic processes is optional in the study of E&M, it is an inherent part of the instruction in modern physics and quantum mechanics. We teach the models that scientists have developed in order to explain macroscopic phenomena. Therefore, to claim an understanding of modern physics concepts, it is crucial that students recognize how macroscopic observations lead to the development of models of microscopic processes and it is essential that they learn the experimental basis for a belief in fundamental particles and their interactions. We believe that students in many of our classes do not understand the link between descriptions of microscopic processes and macroscopic observations, that they learn to memorize explanations and formulae, and develop mental images of microscopic particles without recognizing that existing scientific models are grounded in experimental evidence.

To help improve the teaching and learning of modern physics we see a need for research that investigates the nature of students' models of microscopic particles and microscopic processes, both before and after instruction. Specifically, this need raises the following research questions:

1) Do students come to modern physics classes with preconceived models of microscopic particles and microscopic processes?
2) Have students developed models of microscopic processes based on observations made during macroscopic experimentation or are their models memorized as facts?
3) How do students develop or alter their models based on experimental evidence?
4) How can instruction be modified to aid student development of models of microscopic processes based on macroscopic observations?

In this paper, we will discuss the results of our initial research that addresses the first three questions. We also will make some comments about the fourth research question.

In an effort to address some of these questions, twelve students in modern physics classes at the university level were interviewed to determine their understanding of three fundamental experiments: the charge to mass ratio of an electron (e/m experiment), electron diffraction and the photoelectric effect. In addition, interactive demonstrations were used as a research tool[3] to probe student understanding of modern physics concepts in two high school physics classes.

The interviews and demonstrations were usually centered around actual laboratory experiments (as opposed to thought experiments, computer simulations or experiments described to the students and not performed), so students could see the macroscopic phenomena they were asked to discuss. The study was not focused on student understanding of a particular concept, but on the nature of students' preconceived models, the type of information that they drew together in order to make a model.

In this paper, the word "model" refers to all aspects of students' thinking. A model is a system of thought that has explanatory power. It may include analogies, metaphors, descriptions, equations and memorized facts, as all of these may be used to explain phenomena. It is not necessarily coherent to the "listener" (interviewer), but there is some semblance of coherence in the mind of the person (student) expressing the model. Properties of mental models are still vigourously debated, however general properties have been listed by some authors[4-5].

Often researchers interview both experts and novices and compare their responses[6-8]. The expert responses are labeled a "model" and the novice responses are labeled as preconceptions, misconceptions, conceptual primitives, disconnected statements of fact, or many of a number of other labels. However, both the expert and the novice are expressing their understanding of concepts that can be used to explain the observed phenomena. In this paper, the word model is applied to all responses, independent of the label (preconception, memorized fact, etc.).

In modern physics, an expert explains macroscopic phenomena through coherent models of microscopic processes. The expert may draw on equations, descriptions, analogies and metaphors. The purpose of this paper is to explore students' models of microscopic processes, to examine their nature (equations, descriptions, analogies, etc.) and see if they are coherent and predictive. It is not intended to define the term "model" in more detail, as that is still under discussion in the Physics Education Research (PER) and cognitive science communities.

II. PRECONCEIVED MODELS OF FUNDAMENTAL PARTICLES AND PROCESSES

Many research groups have begun their studies of student understanding of modern physics concepts by asking students to describe or discuss an electron, a photon or the structure of an atom[9-11]. In the study described in this paper, high school students, college students and university physics professors were asked the question, "What is an electron?" Sample answers are given in Appendix I.

This type of inquiry answers the question of whether students have preconceived models of fundamental particles with a resounding "yes". However, that is all it answers.

Although it is a starting point, it is not a fundamental question to ask as part of research in physics education because it does not explore the basis for that understanding. More interesting are questions that explore how students develop and alter their models of microscopic particles and processes before, during and after instruction and the extent to which they realize the macroscopic basis for their models. The rest of the paper is focused on these more fundamental questions.

III. EXPLORING THE BASIS OF STUDENTS' MODELS OF MICROSCOPIC PROCESSES: EXAMPLES FROM THE CHARGE TO MASS RATIO OF THE ELECTRON EXPERIMENT

Four college students in a modern physics class were interviewed after they had done a laboratory experiment on the charge to mass ratio of an electron (e/m experiment). In addition to the laboratory, they had studied the historical experiment done by J.J. Thompson and related topics typically taught in a modern physics class. There was no pre-interview of the students and no special instruction. The interviews took place near the end of the semester, a few weeks after they had done the laboratory experiment.

The e/m experiment consists of an electron tube between two Helmholtz coils. The electron tube contains a trace of inert gas. In the lower half of the tube, electrons leave the cathode (heated filament) and are accelerated through a potential difference to the anode (a plate with a hole in the middle, located about halfway up the tube). If there is no current through the Helmholtz coils, one sees a blue beam come straight up through the hole in the plate. When the coils are turned on, creating a magnetic field perpendicular to the beam, the beam bends over and hits the plate, which is coated with a material that fluoresces when struck by electrons. By adjusting the potential difference between cathode and anode, one can make the beam curve in circles of different radii.

In the interviews, the students were first asked to describe as much of the experiment as they remembered and to explain what happened as best they could. They all remembered what they had seen, but their explanations of the physics varied. The answers ranged from an explanation that involved the Helmholtz coils creating an electric field to a correct qualitative explanation, backed by a description of a quantitative calculation of the e/m ratio. All of the descriptions assumed that the visible blue beam consisted of electrons, without explaining how one knew that to be the case.

The next questions were designed to probe why they assumed the beam consisted of electrons. At this point some of them recognized that they had never raised the question during their experimentation. They responded:

"(Smile) Because the lab manual said they were electrons."

"We were told the blue beam was an electron beam."

"Because we applied a potential difference and electrons do all the moving. Electrons are handy like that."

In response to the question of whether they could distinguish the beam from a beam of light, if they didn't know about how the beam was created, two of them suggested reflecting the beam off of a surface. They said that light would be reflected, but the electrons would pass through. One suggested applying an electric field or even simply holding a charged rod nearby to see if the beam would be deflected. He said that if it were a beam of charged particles that it would be deflected, but if it were a beam of light it would not, because photons are not charged. The fourth student simply said turn on the magnetic field. If the particles are charged, they will bend in a circle. Photons would not do that.

They were then asked if electrons were blue, since they seemed to think that the blue beam they saw consisted of electrons. One answered, *"We never talked about this. I guess its heating up the air its traveling through."* Another said *"Electrons are emitting a wave,"* but could not give a mechanism for this, *"since electrons don't have shells like atoms."* A third said, *" The wavelength of the electrons would cause a blue beam. We could change the wavelength by changing the potential difference which would change the energy of the electrons."* This student was referring to the deBroglie wavelength of the electron as being responsible for the visible light. The fourth said, *" The electrons must be emitting light or hitting something in air that might be emitting light."*

It was clear from questioning that they did not know that the tube contained a trace of inert gas. After this was determined, they were told of the small amount of gas in the tube and asked if this was important to the experiment. Two replied *"if there was a lot of gas, the electrons would deflect off the nuclei and the beam would diffuse."* The other two responses were: *"Gas would claim electrons and the electrons in the gas would move between the energy levels of the atoms and we would see light,"* and *"The electrons in the atom jump to a higher level and give off light. I don't know how the energy is transferred* *from the electron to the atom, causing the electron to become excited, but they go back down and emit light."* Here we find evidence of models of microscipic processes.

Many more questions were asked in the interviews, focusing on concepts that had not been discussed during their experimentation, and watching how they created models and mechanisms to formulate answers. In summary, two things stood out:
1) Many of the questions asked by the interviewer focused on an interpretation of macroscopic observations in terms of a microscopic model. The interviewer asked " how do we know" and "why do we believe" type questions. These questions had not been raised during instruction and they had not occurred to the students. For example, all of them assumed the beam of blue light consisted of electrons because they had been told that. None had pondered the question of why a visible, well focused, blue beam indicates a stream of electrons. The microscopic mechanism for the macroscopic phenomena was missing.
2) They recognized that much of their knowledge was memorized facts and began to alter their memorized models by developing new ones. The new models were based on a combination of their observations and pieces of information that they had learned either in physics class or elsewhere. Often they found that their pieces of information were incomplete and that they did not have a consistent model. The fractured models that the students developed, were an indication that they have trouble developing coherent models themselves, if that development is not stressed during instruction.

IV. ON THE DEVELOPMENT AND ALTERATION OF MODELS: EXAMPLES FROM ELECTRON DIFFRACTION

A. High School Students

Interactive demonstrations were used as a research tool to elicit high school students' ideas about electron diffraction. The students wrote on written questionnaires during the demonstrations and discussions. A copy of the questionnaire is in Appendix IIa. Possible correct answers to the questionnaire are given in Appendix IIb. The students had not studied modern physics. They had studied interference and diffraction of light previously in the course and had observed a diffraction pattern on a screen when a laser beam was sent through two slits.

The students were asked to predict the pattern that would appear on the screen in a double slit experiment with electrons. Of 30 students, 15 said the pattern would be identical to or similar to that of light. They did not give detailed explanations, but some answered enough to give an idea of how they were thinking about it:
"Electrons may bounce off each other and spread out on the screen."
"It would look the same for the most part because all light is made up of many charged particles."
"Electrons would appear in a pattern opposite that of light since they have a negative charge."

The last two are very common conceptions, as will be reported in the section on the photoelectric effect. They were using a description of an interaction between particles (usually charged particles) as a mechanism for the creation of a diffraction pattern. Their previous discussion of the diffraction of light had used a wave model to account for the effect. Only one student related his description to what he had learned about light:
"Electrons sometimes act like waves and when waves pass through slits like these, they spread out."

Of the remaining 15 students, 12 students thought that two spots would be seen on the screen. Their explanations ran like:
"I think it would be two spots because of the fact that the electrons would be separated into two groups and because they are negative the two groups would repel one another."
"Because the electrons can only go through one at a time, they must go straight through or not at all."
Three students left it blank or had ambiguous explanations.

The students were then asked if the pattern on the screen would look any different if the electrons were sent through one at a time. Of the 15 that had initially answered that there would be some kind of interference pattern for a beam of electrons, only four thought that there would be an interference pattern in this case. The rest decided that:
"...there's only one electron going through so there wouldn't be any interference."
"Yes there would only be one spot on the screen. If all the electrons come in the same and are refracted the same, they would all hit in the same spot."
"I think it would be different because it takes nuclear energy (fission of fusion) to split an electron and so it wouldn't be able to divide into two parts to go through the slits, it would go through one slit."

The students were being asked to build mental models for a situation that they had not studied. They followed one of two paths in their process of building a model:

1) They related it to a case they had seen, the diffraction of light. They predicted the same macroscopic phenomenon but invented a new microscopic process to account for it. When asked about a second scenario, electrons passing through the slits one at a time, they chose a new macroscopic result to match their microscopic picture.

2) They immediately distinguished the electron case from the case with light, since their mental model held that electrons were particles and light was a wave. By their particle model, the electrons had to pass through one slit or the other, forming two spots on the screen, whether they went through one at a time or not.

B. College students

Eight students in a modern physics class were interviewed on the topic of electron diffraction. The students were interviewed in groups of four (a group interview) before and after instruction on the subject, including a laboratory. Both the pre- and post-interviews centered around an apparatus for performing an electron diffraction experiment.

The apparatus consisted of a tube with a luminescent screen at one end. In the tube, electrons were accelerated from the cathode to a target which consisted of a thin layer of powdered graphite and continued on to the screen. A diffraction pattern of two rings centered about a central bright spot appeared on the screen.

In the pre-interview, the experimental set-up was shown and described to the students and they were asked to predict the pattern on the screen before the experiment was demonstrated. One of the two groups of students decided that most of the electrons would pass through the carbon undeflected, but that a few would be deflected by the electron clouds in the crystal. This would cause them to curve away from a straight path and the screen would have a bright spot in the middle which would fade as you got further from the center. The second group predicted a pattern with some kind of symmetry, although they disagreed on the pattern. One person said you would see concentric circles, brighter in the center; another said some kind of lattice pattern, like the structure of carbon atoms, little hexagons in a circular pattern. They agreed that you would see a pattern because the carbon atoms have some kind of structure. The electrons would bounce off the carbon atoms in different directions, but not in a random manner. Even the person who had the correct description of how the screen would look accounted for it by a particle model of electrons bouncing off of carbon atoms, like bouncing baseballs off of a polyhedron.

They were then shown the experiment (still before instruction in electron diffraction) and asked to reconsider their responses. The group that had predicted a bright spot, which faded with distance from the center first thought that their explanation of electrons being deflected by the electron clouds of the carbon atoms accounted for the rings. Then they decided that it really looked like a diffraction pattern. They discussed x-ray and laser diffraction patterns and decided that maybe the electron travels like a wave. They said they had learned that light had particle like properties, so maybe an electron had wavelike properties because it is small and moving fast. But they couldn't really describe the wavelike nature of the electron. When asked to consider a double slit experiment with electrons, the explanation they gave for an interference pattern was that the electrons collided with each other, bunching up in some places, moving away in others.

The second group maintained their previous position: a particle model of electrons bouncing off of atoms. They were somewhat surprised that there were only two rings, having expected more from their model of carbon atoms as polyhedrons. It did not occur to them that the bright rings were a diffraction pattern.

The students were instructed with a focus on asking "how do we know" and "why do we believe" type questions. The instructor drew heavily on books and teaching philosophy by Arnold Arons[12]. After instruction, the students were interviewed again, in the same groups. Both groups knew that an interference pattern would appear on the screen in the case of the laboratory experiment they had performed and for a double slit experiment with electrons. They knew the results of a double slit experiment with and without a detector to observe through which slit the electrons traveled, and even the results if you sometimes observed through which slit the electron traveled. Both groups had similar explanations for the microscopic mechanism. They first said that each electron acted like a wave and that the waves interfered with each other. Then someone in the group remembered the result of the double slit experiment when electrons were sent through one at a time and they discussed the possibility that the electron interfered with itself. In one group, there was some argument about the wording "an electron interferes with itself". Finally someone in the group said that it means that the electron has equal probability to go through either slit. Aside from this, they were weak on explaining the phenomena in terms of the wavefunction as an amplitude for the location of the electron and preferred a mental picture of a wave instead. They did have trouble explaining why there were rings instead of discrete points for the electron diffraction apparatus with a powdered graphite target.

They also expressed discomfort with the ideas they were learning:
"My mind wants to think classical mechanically, but at some point, you just have to accept it."
"Although I can't grasp it totally, everything fits together experimentally, so it must be true."
"Right now I agree with it and work with it, but if someone told me quantum mechanics was wrong, I wouldn't be surprised."

The college students developed similar models to those of the high school students before instruction. Both groups of students drew heavily on their previous knowledge of physics, trying to apply information learned in mechanics and E&M. The college students, after instruction, moved closer to a paradigmatic explanation (We don't have information on the high school students after instruction.). These students had been taught with a focus on asking "how do we know" and "why do we believe" type questions. They understood that the accepted microscopic models explained a wide range of macroscopic phenomena. Still, they expressed uncertainty about quantum mechanical ideas.

V. THE AFFECT OF STUDENTS PRECONCEIVED MODELS ON THE STUDY OF MODERN PHYSICS CONCEPTS: EXAMPLES FROM THE PHOTOELECTRIC EFFECT

Eight college students in a modern physics class were interviewed individually before and after instruction in the photoelectric effect. The same apparatus was used for both the pre- and post- interview. It consisted of a carbon arc lamp and an electroscope with a piece of zinc attached to the top. The students were told that the carbon arc lamp emitted both UV and visible radiation. Three cases were demonstrated:
1) The electroscope was charged negatively and then light from the carbon arc lamp was shone on it. This discharged the electroscope.
2) The electroscope was charged positively and then light from the carbon arc lamp was shone on it. There was no significant change in the electroscope.

3) The electroscope was charged negatively and a piece of glass was placed between the arc lamp and the electroscope when the light was shone on it. There was no significant change in the electroscope.

In the interviews, the students were first asked to describe what happened and then to explain why. Questions were also asked to probe the students' understanding of the concepts of light, intensity, energy and frequency as related to the photoelectric effect. The questions were very open-ended. In between the pre- and post- interviews, the students received instruction in the photoelectric effect and did a laboratory experiment similar to Lenard's 1902 experiment[13], using a mercury arc lamp for a light source, a diaphragm to change the intensity and filters to pick out different wavelengths of light. This allowed them to determine that the stopping potential was independent of intensity, but did depend on frequency. In class they also discussed the fact that Lenard did not find a threshold intensity, which the classical theory predicted. The nature of the class was to focus on asking "how do we know" and "why do we believe" type questions. The post-interview was similar to the pre-interview, except that the students were also asked about the experiment they had done in the laboratory and to plot graphs of current vs. potential difference and stopping potential vs. frequency.

A. Pre-interview results

In the pre-interviews, 5 of 8 students thought that some type of positive charge was being emitted by the carbon arc lamp. Some said that photons were charged. Others thought the photons were dragging positively charged particles along with them. They said that the positively charged particles were: 1) attracted to the negatively charged electroscope, causing it to discharge, 2) repelled from the positively charged electroscope and, 3) stopped by the piece of glass placed between the arc lamp and electroscope. The incorrect models were very consistent, accounting for all of the observed phenomena. They were based mostly on concepts learned in E&M classes.

Three students did answer correctly. They discussed light in terms of photons with energy determined by the frequency of the light. They said it was the UV photons that caused the effect and that some electrons would be ejected even at low intensities.

B. Post-interview results

In the post interviews, all students answered most questions correctly. They attributed the effect to UV photons. They did not think there was a stopping intensity, but that there was a threshold frequency. They could correctly graph current vs. potential difference for different intensities and stopping potential vs. frequency for the experiment they had performed in the laboratory.

They had difficulty with the case of the positively charged electroscope. They struggled to explain why the electroscope leaf did not rise. Four of the eight students thought either that there were very few electrons in a positively charged electroscope or that the electrons were more tightly bound in that case, making it harder to eject electrons.

C. Follow-up with other college students

To make sure that the high percentage of students who said that light consisted of charged particles or carried charged particles with it was not a statistical fluctuation, eighteen students who were near the end of a course in E&M were also surveyed. They were shown the carbon arc lamp experiment in class and asked to explain each case on a written questionnaire. The questionnaire is shown in Appendix IIIa. Possible correct answers to the questionnaire are given in Appendix IIIb.

Seven students did not write enough for us to determine their models. Of the eleven who wrote enough to give us an idea of their model, eight believed that the electroscope discharged because positively charged particles were emitted from the carbon arc lamp.

D. Follow-up with high school students

Interactive demonstrations were used as a research tool in a high school class that had studied the photoelectric effect. This occurred after some instruction in modern physics concepts. Forty-five students answered the questions on the questionnaire in Appendix IIIa during the interactive demonstration and discussion.

About one quarter of the students answered completely correctly for a negatively charged electroscope. None of them answered completely correctly for the case of a positively charged electroscope, although one had the right idea. Seven of forty-five thought that the carbon arc lamp emitted positive charges and eight thought it emitted negative charges. There were also a number of other explanations.

Although the high school students did not participate in a pre-interview, it is reasonable to believe that they would have developed models similar to the college students before instruction, based on their previous knowledge of mechanics and E&M. In the case of the college students, there was evidence that the incorrect model had been completely replaced by a correct model after instruction, leading one to believe that this was not a tenacious preconception, simply a reasonable incorrect model, replaced by effective instruction. However, this was not true for the high school students. They did not use the modern physics concepts they had learned to explain the phenomena. They reverted to explanations in terms of classical mechanics and E&M. The college students were taught with a focus on "how do we know" and "why do we believe" type questions; they were taught to think about reasons for microscopic models. Detailed information on the teaching approach in the high school class was not available. So, we cannot, based on this study, determine if the difference observed in the two groups was due to the method of instruction, to the age of the students, or other factors.

VI. CONCLUSIONS

The exploration of students' development of models of microscopic processes outlined above, leads to the following observations and bases for further research:
1) Students have preconceptions (mental models developed before instruction in modern physics) of microscopic processes. These are often memorized "facts", not grounded in an understanding of the desirability of the model based on observed macroscopic phenomena.
2) When posed with the question of explaining the results of an experiment that demonstrates a modern physics concept, the students are aware of the need for a model of microscopic particles and processes, even before instruction in modern physics. They build models consistent with their own models of microscopic processes and their prior knowledge of E&M and mechanics. These models are often incorrect, but self consistent (within a certain experiment). Students who have been introduced to modern physics concepts, but have not learned about the basis for the development of models of microscopic processes, offer fragmented models, built primarily of memorized facts.
3) There is some evidence that instruction in modern physics should include an emphasis on linking models of microscopic processes to macroscopic observations. When that does not occur, students have trouble developing coherent models themselves; they often revert

to preconceptions based on E&M and mechanics concepts, which they find more plausible than quantum mechanical explanations.

These conclusions imply that there is a need to develop modern physics curricula that are structured around building models of microscopic processes grounded in macroscopic observations, stressing the advantages of quantum mechanical modeling to explain experimental results. Research should be used to determine particular student difficulties in understanding the physics concepts <u>and</u> to develop methods for helping students develop consistent models.

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Appendix I: Answers to the question "What is an electron?"

Typical answers from high school students:

"A particle in an atom on the outside ring with a negative charge."

"Negative charged energy that moves about the electron cloud (outer portion) of an atom."

"An electron is a negatively charged particle."

" It's kind of a three dimensional wave or pulse. It has almost no weight and it's the reason atoms react with each other."

" A subatomic particle with a mass approximately 1/1800th of an amu. It contains a negative charge. It orbits the nucleus and it is said to have a counterpart known as a positron. They also affect the stability of an atom."

"An electron is a particle or a wave with a negative charge and a mass that is almost zero, so the mass is often ignored. It is the part of an atom that travels around the nucleus in energy levels and orbitals. It has spin."

"A negatively charged particle in an atom, an electron has no mass. When light is given off, it is because the electrons in an atom become excited, jump to a higher level, and then eventually return to the ground state, and that is when light is given off. They are also attracted to protons."

Typical answers from college students:

" An electron is an infinitesimally small particle with a mass and a charge. ... The electron is a subatomic particle, which orbits the nucleus of an atom, which is made up of protons and neutrons. At this time, we ignore quarks, etc. and hold to the more classical view of the atom. An electron can exist separately from an atom and is called a free electron."

"A particle with a mass, a negative charge and can be found somewhere around the nucleus of atoms."

" An electron is a negatively charged particle that orbits the nucleus of an atom in an electron cloud. It does this unless forced otherwise. It has a mass of 9.1×10^{-31} *kg and a charge of* 1.6×10^{-19} *C. Travels near the speed of light.'*

Answers from some university physics professors:

"It's a charged particle."

"An electron is elusive like a photon; we can only determine its properties."

"An electron is a solution to a certain second order partial differential equation in an abstract multidimensional space."

Appendix IIa: Written questionnaire on electron diffraction

1) Answer, in your own words, the question "What is an electron?"

2) If a beam of electrons were sent through a double slit, what would the pattern on a fluorescent screen look like? Assume that the slits are not much wider than the spacing between atoms in a solid. Draw the pattern that would appear on the screen. Explain your reasoning.

[Insert Fig. 1. here]

3) If the electrons were sent through one at a time, would the pattern on the screen be any different? Explain your reasoning.

4) Would the pattern be different if only ten electrons were sent through, instead of 1000 or 1,000,000? How would it be different? Draw the different patterns that would appear on the screen in each case.

Appendix IIb: Possible correct answers to the written questionnaire on electron diffraction

1) Answer, in your own words, the question "What is an electron?"

2) If a beam of electrons were sent through a double slit, what would the pattern on a fluorescent screen look like? Assume that the slits are not much wider than the spacing between atoms in a solid. Draw the pattern that would appear on the screen. Explain your reasoning.

[Insert Fig. 1. here]

The pattern that would appear on the screen would be a set of bright fringes, equally spaced, with dark spaces in between. Superposed on this pattern would be a single slit diffraction pattern, so the middle fringe would appear brightest and there would be some tapering in intensity of the fringes, dependent on the slit width.

[Insert Fig. 2. here]

An electron can be represented by a wave function. The square of the wave function is a probability distribution representing the probability that the electron would be found at a certain point in space and time, if a measurement were made. The amplitude of the wave function, as the electron moves through the slits and to the screen, exhibits interference, just as a water wave (for example) would, as it passes through two slits. Since the amplitude of the wave function exhibits interference, the probability distribution of where the electron would be found, if a measurement were made, demonstrates this interference. The electron is more likely to be found in some places and has very little probability of being found in others.

3) If the electrons were sent through one at a time, would the pattern on the screen be any different? Explain your reasoning.

If the electrons were sent through one at a time, each electron would be detected at the screen at one point. It would be more probable that the electron would be detected at the screen at one of the bright fringes in the diagram above. As more and more electrons were sent through, the above pattern would emerge.

4) Would the pattern be different if only ten electrons were sent through, instead of 1000 or 1,000,000? How would it be different? Draw the different patterns that would appear on the screen in each case.

The pattern for ten electrons might look like:

[Insert Fig. 3. here]

The pattern for 1,000,000 electrons would appear as above.

Appendix IIIa: Written questionnaire on the photoelectric effect

In the front of the room is an electroscope with a piece of metal attached to it, a carbon arc lamp, a diaphragm and a piece of glass. The carbon arc lamp produces both ultraviolet (UV) and visible radiation. You will see three experiments performed.

Experiment 1) The electroscope is charged negatively and then light from the carbon arc lamp is shone on the electroscope.

Describe what happened.

How would you explain this result? Give as much detail as possible.

Predict what would happen if the intensity of light were decreased. Would you see the same effect? For example, if the diaphragm were placed between the arc lamp and the electroscope and closed down to a very small opening, would anything change?

Experiment 2) The electroscope is charged positively and then light from the carbon arc lamp is shone on the electroscope.

Describe what happened.

How would you explain this result? Give as much detail as possible.

Experiment 3) The electroscope is again charged negatively. Then light from the carbon arc lamp is shone through a piece of glass on to the electroscope.

Describe what happened.

How would you explain this result? Give as much detail as possible.

Do you think that if you increased the intensity of the light that you would see a different effect (with the light still passing through the glass)?

Appendix IIIb: Possible correct answers to the written questionnaire on the photoelectric effect

In the front of the room is an electroscope with a piece of metal attached to it, a carbon arc lamp, a diaphragm and a piece of glass. The carbon arc lamp produces both ultraviolet (UV) and visible radiation. You will see three experiments performed.

Experiment 1) The electroscope is charged negatively and then light from the carbon arc lamp is shone on the electroscope.

Describe what happened.

The leaves of the electroscope moved apart when the electroscope was charged and moved together when the light from the carbon arc lamp was shone on the electroscope.

How would you explain this result? Give as much detail as possible.

Light consists of photons, massless particles with energy and momentum. A photon's energy is proportional to its frequency. The photons could interact with the electrons in the metal of the electroscope. If a photon had enough energy, it would be possible for it to interact with an electron in the metal and transfer sufficient energy to the electron to remove the electron from an atom. An electron removed from an atom in the metal of the electroscope would be repelled from the negatively charged electroscope. If many electrons were removed from the electroscope, the electroscope would discharge.

Predict what would happen if the intensity of light were decreased. Would you see the same effect? For example, if the diaphragm were placed between the arc lamp and the electroscope and closed down to a very small opening, would anything change?

If the intensity of light were decreased, less photons would interact with the metal in a given time interval. However, if the light emitted the same frequencies, the photons would still have enough energy to remove electrons from the metal. There would simply be less electrons emitted from the metal in a given time interval. So the electroscope would not discharge as quickly.

Experiment 2) The electroscope is charged positively and then light from the carbon arc lamp is shone on the electroscope.

Describe what happened.

The leaves of the electroscope moved apart when the electroscope was charged and then there was very little motion of the leaves of the electroscope when the light from the carbon arc lamp was shone on the electroscope.

How would you explain this result? Give as much detail as possible.

As stated above, light consists of photons. The photons could interact with the electrons in the metal of the electroscope. If a photon had enough energy, it would be possible for it to interact with an electron in the metal and transfer sufficient energy to the electron to remove the electron from an atom. However, an electron removed from an atom in the metal of a positively charged electroscope would be attracted to the electroscope, so the electroscope would not become more positively charged.

Experiment 3) The electroscope is again charged negatively. Then light from the carbon arc lamp is shone through a piece of glass on to the electroscope.

Describe what happened.

The leaves of the electroscope moved apart when the electroscope was charged and then there was very little motion of the leaves of the electroscope when the light from the carbon arc lamp was shone on the electroscope.

How would you explain this result? Give as much detail as possible.

The glass blocks the photons that have enough energy to remove an electron from an atom. Since the more energetic photons are blocked by the glass, the electrons remain in the metal and the electroscope remains negatively charged.

Do you think that if you increased the intensity of the light that you would see a different effect (with the light still passing through the glass)?

The glass successfully blocks most of the photons with enough energy to remove an electron from an atom at the original intensity; some of the more energetic photons pass through the glass, but not enough to see the effect. As the intensity is increased, more of the photons with enough energy to remove an electron from an atom will pass through the glass. You may see the effect at reasonable intensities, but it will take a longer time for the electroscope to discharge.

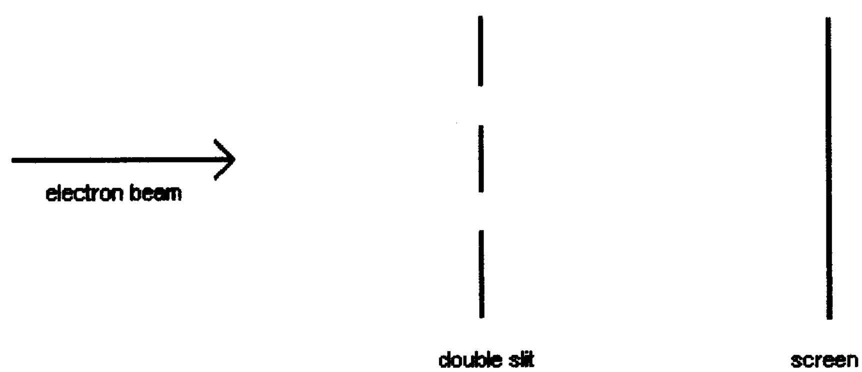

Fig. 1

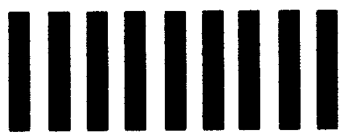

Fig. 2

Fig. 3