DOCUMENT RESUME

ED 414 197 SE 060 983

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| AUTHOR | Mashhadi, Azam |
| TITLE | Advanced Level Physics Students' Conceptions of Quantum Physics. |
| PUB DATE | 1995-00-00 |
| NOTE | 13p.; Paper presented at the Annual Meeting of the Singapore Educational Research Association (9th, Singapore, November 22-24, 1995). |
| PUB TYPE | Reports - Research (143) -- Speeches/Meeting Papers (150) |
| EDRS PRICE | MF01/PC01 Plus Postage. |
| DESCRIPTORS | Cognitive Psychology; *Cognitive Structures; Concept Formation; *Constructivism (Learning); *Epistemology; Foreign Countries; Higher Education; Knowledge Representation; Learning Strategies; *Learning Theories; Models; *Quantum Mechanics; Science Education; Secondary Education; Thinking Skills |
| IDENTIFIERS | Analogies; Great Britain |

ABSTRACT

This study addresses questions about particle physics that focus on the nature of electrons. Speculations as to whether they are more like particles or waves or like neither illustrate the difficulties with which students are confronted when trying to incorporate the concepts of quantum physics into their overall conceptual framework. Such questions illustrate the difficulties in using analogies taken from ordinary experience, described mostly by classical models, in explaining the subatomic world. Data for this study were obtained from a semi-structured questionnaire completed by physics students (N=57). The questionnaire consisted of open and closed questions, drawings of particular situations, and attitude scales. Findings indicate that students are inclined to incorporate the new quantum phenomena into the older mechanistic conceptions and that most students are not epistemologically aware that quantum physics constitutes a new paradigm. Contains 16 references. (Author/DDR)

*Paper presented at the Singapore Educational Research Association 9th Annual Conference, 22-24 November 1995.*

# Advanced level Physics students' conceptions of Quantum Physics

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**Abstract**

> ...I think I can safely say that no one understands quantum mechanics ....do not keep saying to yourself, if you possibly can avoid it, 'But how can it be like that?' because you will get 'down the drain', into a blind alley from which nobody has yet escaped. Nobody knows how it can be like that.
> Richard Feynman (1967: 129)

Especially over the last fifteen years there has been considerable research interest in the student's perceptions of phenomena in such areas as energy, motion, the particulate nature of matter, electricity, and light. However, ninety years after the genesis of Quantum Physics significant research on *students' understanding* of such revolutionary phenomena is only beginning to emerge.

What are electrons really like? Are they like particles or waves? Are they like both particles *and* waves, or like neither? These questions illustrate the psychological difficulties with which students are confronted when trying to incorporate the concepts of Quantum Physics into their over-all conceptual framework. They also illustrate the difficulties in using analogies taken from ordinary experience (i.e. essentially classical models) to 'explain' the subatomic world. In its predictive abilities Quantum Theory is the most successful physical theory that has ever been conceptualised, and forms the basis of high technology industries. However Einstein once remarked that Quantum Theory reminded him of 'the system of delusions of an exceedingly intelligent paranoiac, concocted of incoherent elements of thought.' (In Arthur Fine, 1986).

Following a review of previous research the initial findings of a study investigating students' understanding of quantum phenomena is presented.

## 1 Introduction

> **Kerner** ....I cannot stand the pictures of atoms they put in schoolbooks, like a little solar system: Bohr's atom. Forget it. You can't make a picture of what Bohr proposed, an electron does not go round like a planet, it is like a moth which was there a moment ago, it gains or loses a quantum of energy and it jumps, and at the moment of the quantum jump it is like two moths, one to be here and one to stop being there; an electron is like twins, each one unique, a unique twin.
> Tom Stoppard (1988: 36), *Hapgood*

This new study is designed to build on and complement previous work carried out principally by research groups in Bremen, and Berlin. The aims of the Students' Conceptions of Quantum Physics Project (SCQP) are to elicit students' conceptions of quantum phenomena, develop a model of cognitive adaptation to a new paradigm, and evaluate the efficacy of the incorporation of quantum physics at the pre-university level. The study should lead to more effective teaching and learning strategies, and inform policy and curriculum decision-making.

The basic ideas of quantum physics are not necessarily difficult as that they are strange. In some situations, electrons that are usually referred to as 'particles' may exhibit 'wave-like' behaviour. Electromagnetic radiation, known classically as a wave phenomena, is explained in terms of particles called photons. Both matter and radiation can be viewed as having a dual (wave-particle) nature. What are electrons *really like*? Are they like particles or waves? Are they like both particles *and* waves, or like neither? These questions illustrate the psychological difficulties with which students are confronted when trying to incorporate the concepts of quantum physics into their over-all conceptual framework.

In less than a century physics has abandoned a world view consisting of concepts that were mechanistic, deterministic and largely absolute, and espoused a world view comprising concepts that are relative, frequently non-deterministic and stochastic in nature (Castro and Fernández, 1987). However the 'Newtonian world-view' still dominates our culture, in spite of its being superseded by relativity theory and quantum mechanics. The Newtonian categories of space, time, matter and causality are deeply embedded in our perception of reality to such an extent that they, arguably, determine every aspect of the way that we think about life. It has been argued that culturally the general public are impoverished by their ignorance of the significance of twentieth century physics. As the 21st century rapidly approaches school physics is essentially quantitative Newtonian physics (i.e. 'classical physics').

At present in the UK, upper secondary school students (ages 16-18) wishing to read for a physical science degree at university will follow the two year Advanced Level Physics course. The quantum physics section of the course syllabus will typically not include the Heisenberg Uncertainty Principle, the Schrödinger wave equation, and there is no explicit mention of introducing students to conceptions of the 'nature of science'.

The difficulties in learning quantum physics have been highlighted by a number of authors. Jones (1991: 93) argues that at A-level students:

> Instead of moving from classical mechanics to quantum mechanics, students move to an uneasy hybrid, mostly composed of ideas and pictures developed in the period 1900-1920, which went under the name of 'old quantum theory'. This produces half-baked and incorrect conceptual models which stunt understanding and the development of interest.

Faucher (1987) highlights the problems university students, in Montreal, have experienced in coming to terms with quantum physics. The principal tactic adopted by students is that of 'pragmatical conceptualisation', students 'usually do not question accepted theories; they accept them as <u>facts</u> very easily after a short period of incubation, where doubt is allowed.' Faucher (1987: 140) argues that these pragmatic conceptions include:

> ...poor conceptualisation of phenomena, weak comprehension of basic classical physics, inability in matching classical and modern physics, inaptitude to face new facts and to make generalisations.....students hold a purely empirical view of science.

Lehrman (1982) and Garcia-Castañeda (1985) have referred to serious conceptual errors which are propagated by introducing modern physics in a very simplistic way. Gil and Solbes (1993: 257), at the *Universitat de València (Spain)*, argue that:

> ...pupils' difficulties in learning modern physics have an epistemological origin; that is to say, they come from an ignorance of the deep conceptual revolution that the emergence of the new paradigm constitutes. Any meaningful learning of the few elements of modern physics introduced in high school would then be obstructed by the linear, accumulative view presented. In brief: modern physics was constructed *against* the classical paradigm, and its meaningful learning would demand a similar approach.

Although speaking in the context of student learning of classical mechanics Champagne *et al.* (1980: 1077) sum up the difficulty of adapting to a new paradigm:

> ...the arduousness of learning mechanics is expressed in the effort required as students shift their thinking from one paradigm to another. Paradigm shifts are not accomplished easily, neither in the scientific enterprise nor in the minds of students.

The language of quantum physics is closely related to the models that are used in quantum physics. There are however a number of linguistic inconsistencies in quanutm physics. Physics text books often include the Bohr model of the atom, which is essentially the representation of the atom as a micro-planetary system, and talk in terms of the electrons moving in the vicinity of the nucleus. Herrmann (1994:3) points out the problems that this gives rise to:

One then assures that one should not imagine a definite trajectory, that the concept of trajectory loses its meaning. But what is, the learner will ask, a movement without a trajectory? As a solution to the enigma pseudo-explications are proposed: The point-like electron is sometimes here, sometimes there, always with a certain probability. It thus moves to the various locations. It does this, however, as we have seen, without following a path. how does it succeed in doing so? Another verbal ritual in this context is that of the uncertainty principle. The position does not have, one learns, a sharp value.

## 2 Previous research findings

The most systematic and extensive research to date has been carried out by a research group headed by Professor Niedderer, based at the University of Bremen, and Fischler and Lichtfeldt, based at the Free University of Berlin. Niedderer (1987: 345) reported on Bormann's (1987) work describing the various conceptions of the wave-particle duality of electrons that students developed in an attempt to reconcile apparently contradictory properties:

(1) The "strict" particle view
Students looked at electrons as particles moving along straight lines. The observations of electron distributions were explained by collisions..
(2) The particle moving along a wave
The electron is a particle (mass, velocity, orbit).
This particle moves along a wave-orbit. The electron is the oscillator of the wave.
(3)The formal wave conception
The diffraction pattern is explained by an electron wave. Either the electron is a wave itself or there is a new kind of wave (which is influenced by a magnetic field).

In addition Bormann works on the following hypotheses:
- The particle view is easier for students to understand than the wave view.
- The electron is a "real" particle, the photon is a sort of "energy particle".
- Photons and electrons are primarily particles which should have some wave properties to explain special sophisticated experiments.

Niedderer, Bethge and Cassens (1990: 77) subsequently went on to provide a summary of some of Bethge's (1988) investigation of grade 13 (age 18-19) students:

**Characteristics of students' own reasoning**
1 Students have a concrete picture of the atom, in terms of mechanics and the everyday life-world.
2 Students tend to use the concepts of movement and trajectory in their own explanations of properties of the atom (even if they deny them!)
3 Students tend to use the concept of energy and mass conservation in their own explanations.
4 On the other hand, students do not spontaneously request further explanations of the existence of discrete energy levels, but tend to use them as a basis for other explanations.

**A second level of description is more related to students' preconceptions**

4A

> 1 Movement (and trajectory) are continuous; for every two points of the movement, the points between also belong to the movement, even if they are not observed. At the beginning and at the end we have the same body, even if we have not watched it in between.
> 2 A trajectory is a definite and ordinary path, such as a circle or an ellipse, but not some strange zig-zag-movement.
> 3 The stability of an atom is the result of a balance between an attractive electric force and the activity (=force or energy!) of the movement of the electron. The electrodynamical problem of stability is not present in students' views.
> 4 Energy is seen as some activity or general cause which is specified in special situations (sometimes as a force, or as energy in a physical meaning or even as a kind of matter).
> 5 Probability is seen as some kind of inaccuracy. If you do not know something exactly, you talk about probability.

Fischler and Lichtfeldt (1992: 187), in Berlin, found that the following conceptions of the 'atom-electron' were found most often in their study of 240 A-level students (*Leistungskurse* course in the upper Gymnasium or grammar school):

> *Circle* (circular orbit): conceptions of electrons which fly round the nucleus with (high) velocity in fixed, prescribed orbits. In this conception the centrifugal force and the Coulomb (electric) force are brought into equilibrium. The students use their experience with roundabouts first to explain the movement of the planet, and then second to explain the process in atomic shells, without regard to reference systems (63% of 240 students in both groups).
> *Charge*: students have a fixed conception of the repulsion between charges. They often explain the properties of charges incorrectly . The charges of both the proton and the electron cause a distance between the two particles (similar to a bi-polar dumbbell). The students assemble a suitable conception from single elements of knowledge (23% of 240 students in both groups).
> *Shell*: conception of a firm casing (shell, ball) on which the electrons are fixed or move (8% of 240 students in both groups).
> [After the unit was taught another "conceptual pattern" was constructed from students' responses:]
> Loc. (localization energy): the stability of atoms was regarded by the students as connected with the Heisenberg uncertainty principle. According to this conception, the mere restriction of space results in a rise of the kinetic energy of the electrons, the loci of which are subjected to a statistical distribution. At the same time the students dispensed with statements about single electrons which they thought of as inconceivable.

The research by the Bremen group indicates that for students mechanical thinking in terms of orbits of classical particles is dominant. Fischler and Lichtfeldt (1991:257), in Berlin, interpreted their study as finding that the:

> ...results of the control group meanwhile pointed to an incorporation of the "new" phenomena into the "old" mechanistic ideas. Here, the different ideas in quantum physics were merely acquired verbally in the science language level and forgotten again afterwards. The conscious top down process of reconstruction which had to be done by the students in the everyday language was not possible for them.

The German educational system is different from that of the UK, and since the 18-19 age group was being considered the research findings may not be directly applicable. The quantum physics section of the A-level physics syllabuses in terms of both the extent and depth of their coverage of the topic is different to the German syllabus. This current study is, therefore, initially concerned with seeing if A-level students' in England hold similar conceptions, and will subsequently be using a larger population sample to quantitatively investigate the grouping of conceptions.

## 3 Initial findings of the SCQP project

This preliminary study consisted of a semi-structured questionnaire completed by A-level Physics students (N = 57) in three Oxfordshire secondary schools in May 1993. The questionnaire utilised open and closed questions, drawings of particular situations, and attitude scales.

*How Do Students View The Atom?*

Following an interpretative analysis of responses to questions concerning 'the atom' (see the Appendix, and Questions C2, C5, and C10), the following broad conceptions of the atom were constructed from the data:

1. mechanistic picture
2. probabilistic picture
3. 'random' motion picture
4. 'smeared charge cloud'
5. no visualisation possible

The **mechanistic** conception (held by ~ 25 per cent of the students) consisted primarily of (many) fast-moving electrons in definite orbits, similar in some ways to the planetary model of the atom:

> Because electrons orbit so fast that we can't tell where one is at any time - therefore it is inaccurate to draw them at one place.
> 22/C10[1]

The planetary model is not necessarily the same as the Bohr model, not only was there no mention of Bohr's postulates but the term 'Bohr model or atom' was not explicitly mentioned by the students. Elements of language from the Bohr atom were used (e.g. electron orbits, energy levels etc.), but it is doubtful if the students actually had the Bohr model in mind. There was an acknowledgement by many students that the planetary model of the atom is a useful picture but also an acknowledgement that there are limitations:

> The analogy has certain likeness but is also dissimilar to the structure of an atom. In a solar system planets are held in orbit by a gravitational force and in an atom electrons are held by an electrostatic force of

[1] The notation 22/C10 indicates that this is student number 22 giving a response to question C10.

attraction. However the nucleus of an atom is massive and many times larger than the electrons. Whereas this size discrepancy is not evident in the solar system. Electrons move between orbital whereas planets don't.
10/C2(b)

The orbit is regarded as the result of a "balance" (as several students expressed it) between the electron's speed and the electrostatic force of attraction between electron and nucleus:

The electron has a negative charge and is travelling at a certain speed. The nucleus has a positive charge and so attracts the electron. This keeps the electron in place and everything is balanced.
3/C5(a)

A significant percentage (~ 25 per cent) regarded electron clouds as providing a **probabilistic picture**, but they still thought in terms of 'the electrons', i.e. as particles:

You can't say where you will find an electron, only draw in areas or more correctly volumes where there is a greater than 95% chance of finding an electron.
43/C10

The Heisenberg Uncertainty Principle does not form part of the syllabus, and the 'standing electron-wave' model, if it is taught at all, is only briefly touched on so it is unclear whether this probability view stems from a recognition of the wave nature of the electron or is viewed as the result of imprecision in measurement or randomness in movement. Further study needs to be undertaken of their conceptions of this, as well as their perception of the nature of 'probability'. One student made a specific reference to Heisenberg:

...I think this is what physicists argue in accordance with Heisenberg's Uncertainty Principle. Although the notion of fundamental uncertainty makes me dubious as to whether quantum mechanics is a complete model of reality.
40/C7(e)

The **'random'** motion picture (~ 23 per cent) consisted of combinations of the mechanistic and probability /random viewpoints involving random movement *within* a bounded region or *at* different energy orbits (a 'shell'):

Electrons do not move in a circle around the nucleus, like a planet does around the sun, instead it moves randomly but in the shape of a certain shell, therefore we can predict that at one instant the electron may be at that point but we can never be sure, therefore they draw a cloud.
46/C10

A very small number (~10 per cent) talked in terms of a '**smeared charge cloud**':

Electrons have no shape they are charge clouds and so could not be individual but all together.
26/C10

When orbiting an atom, the electron does not occupy only one space at any one time but instead is "spread out" all around its orbit.
32/C10

In addition a (very) few students (~5 per cent) argued that **visualisation was not possible**:

> ...I believe it is very difficult if not impossible to conceive what is actually going on. Our visual models are derived from experience through evolution of the environment we are in the world of miniature particles is totally alien to us.
> 40/C7(g)

*How Do Students View Electrons?*

The conceptual hurdles that students face was expressed quite succinctly by a student:

> Electrons you always think of as particles from age 12 - 6th form, light is always explained as a wave from age 5 - 6th form, you have had a long time to think of one thing before it is even mentioned that it is possible that may not be completely true.
> 43/C7(f)

How do students view electrons or the behaviour of electrons when faced with a diffraction effect? Two of the questions focused on the 'electron diffraction tube', and a situation in which electrons encounter a single slit (see the Appendix, Questions C7 and C8). Students' conceptions of the electron when faced with phenomena that illustrates their 'wave behaviour' are quite tangled. Certain broad conceptions do, however, emerge with electrons regarded as:

1. 'classical' particles
2. waves
3. linked to 'probability waves'
4. 'smeared charge'
5. cannot be visualised

Many students, just under a third, still adhered strongly to the **classical** particle or 'electron-**as-particle'** viewpoint, with electrons having a definite trajectory. Comments included:

> This implies that electrons are waves, and so must be nonsense because electrons behave like particles, therefore cannot interfere either constructively or destructively.
> 18/C7(c)

Students with this classical viewpoint adopted a straight line path (in response to Question C8), with the electrons hitting the screen at one point. Typical comments included:

> As the slit is so large compared to an electron, I think that they will be unaffected by it and all hit the screen in the same place.
> 15/C8

In their responses to the diffraction tube roughly two-thirds of the students associated electrons with **waves,** and talked in various ways of 'electron diffraction/interference'.

However this is quite a broad conception, and it is unclear whether they are thinking in terms of electrons as particles with wave properties, particles that turn into waves, or electrons as waves that interfere. Typical comments included:

> The electrons are behaving like waves, however the nuclei of the graphite atoms are acting on the electric charge of the electron and diffracting them, the electron waves then meet in certain places and interfere.
> 32/C7(d)

One student made explicit reference to the 'standing wave' model of the electron-atom:

> The energy of the electron. The electron forms a standing wave around the nucleus. If it were to approach closer, the standing wave would be disrupted.
> 42/C5(a)

Only a few of the students (~ 4 per cent) talked explicitly in terms of a **'probability wave'**:

> The path of a particle is undetermined. There are an infinite number of paths, with paths of destructive interference having the least probability, and vice versa. The path that the electron takes is governed by this probability, and can only be determined when it strikes the screen, i.e. its wave properties are "removed".
> 42/C7(c)

Another minority viewpoint (~4 per cent) regarded electrons as consisting of **'smeared charge'**:

> They consist of smeared charge at different distances from the nucleus.
> 20/C7(a)

A very small number of students (~ 4 per cent) argued that **visualisation is neither possible nor desirable**:

> ...unfortunately all that is known about electrons is just theory because no one can ever see an electron because these are smaller than the wavelength of visible light. So really, it is just a case of whichever theory makes the most correct predictions.
> 32/C7(b)

## 4 Conclusions

The students, largely, are not conscious of their own conceptions and consequently do not begin to question them. The preliminary results of the study indicate that students have incorporated the 'new' quantum phenomena into the 'older' mechanistic conceptions. Further work will need to be done, but the current data implies that most students are not epistemologically aware that quantum physics constitutes a new 'paradigm'.

The preliminary results are generally consistent with previous research in other countries. Further work is being carried out to elicit students' conceptions of figurative language (i.e. the nature of models) and their perceptions of the nature of theoretical entites, and to investigate the interrelationships between conceptions.

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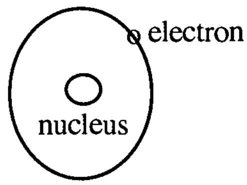
## 6 Appendix : Questionnaire

C2 People sometimes say that the structure of the atom is similar to the structure of the solar system (i.e. the planets in orbit around the Sun).
(a) Do you agree with this? (b) Explain your answer.

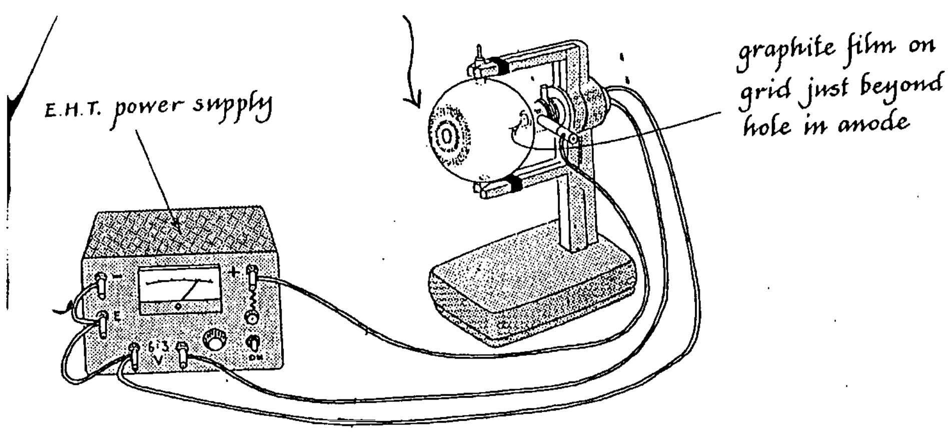
C5 (a) In many textbooks there is a diagram like the one below, in which an electron is said to be in orbit around the nucleus of the atom. Explain how the electron stays in orbit.




(b) What do you think lies between the nucleus of an atom and its electrons?
(c) Is this sort of diagram useful, or is it misleading? Does it give people the wrong idea about atoms?

C6 In one of the physics textbooks it says that J.J.Thomson **discovered** the electron in 1895. A student on reading this remarked that J.J.Thomson **invented** the electron. What do you think? Why should the student have felt that the electron was invented, and not discovered?

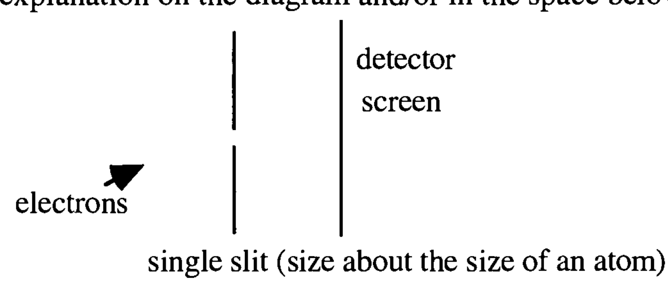
C7 The diagram below shows an apparatus in which a beam of electrons is accelerated in an electron gun to a potential of between 3500 and 5000 V and then allowed to fall onto a very thin sheet of graphite. Graphite consists of regularly spaced carbon atoms. As you can see a pattern of concentric rings is produced on the fluorescent screen.




Students A says,"The pattern isn't being produced by electrons, but by light given off from the hot cathode."
He argues that he can show this to be the case by holding a magnet next to the pattern. Light is not affected by a magnetic field, and so he argues the pattern will stay unchanged.
However, to his surprise, when he carries out the experiment, the **pattern is deflected.**
(a) Student B then says,"These rings are a diffraction pattern. The sheet of graphite is acting just like a diffraction grating."
**If** this were the case what would it indicate about the nature of electrons?
(b) At this point student C says," That's nonsense, electrons are particles and also negatively charges. Electrons are always repelling each other, and even if tow

electrons were to collide they would just bounce off each other. There shouldn't be any pattern at all with electrons. Something else is happening."
Do you agree or disagree with this? Explain your choice.
(c) Student D forcefully points out," Electrons are being shot out of the electron gun. The pattern was deflected by a magnet, so whatever it is must have an electrical charge. That means it isn't due to light being diffracted. That only leaves the electrons. That must mean that **the electrons** are constructively and destructively interfering with each other."
What do you think? Does this sound reasonable or 'nonsense'?
(d) Student B then says,"The chemical on the detector screen is glowing brightly whenever an electron hits it and transfers its kinetic energy. So there are places where there are electrons striking the screen, and laces where electrons are not striking the screen. The brighter the ring, the greater the number of electrons hitting that area."
The teacher, at this point, asks the class,"If this is the case then how come there are areas where the electrons are going to and areas where electrons are not going to?"
What answer would you give?
(e) Having thought about the situation very carefully, student A says,"If we want to find out where electrons are then they are most likely to be where there are bright rings, glowing on the chemical coating the end of the tube. In other words the rings are telling us the likelihood or the probability of where the electrons are most likely to strike the detector."
Does this sound reasonable? Do you agree or disagree (and why) with his argument?
(f) Student C remarks,"The pattern does look very like the diffraction patterns we were getting when we looked at the diffraction of light. But this must be just a coincidence, as light and electrons are very different things."
Why should he say this? Do you agree with him?
(g) Student B then says she is very confused by this experiment, and that she is going to adopt the attitude that there is no point in thinking about what electrons are really like or about what they are doing once they leave the electron gun. She is just going to look up in the textbook the formula which will tell her at what points on the end of the tube the electrons will most likely be at (i.e. the formula which will predict he shape of the pattern), and then just use that formula if she is asked to do any calculations.
What do you think of her attitude or approach? Do you agree with it, or not? Explain your answer as fully as possible.
(h) Student A says that they don't know enough about the situation or about electrons. If they knew more they could explain everything perfectly. What do you think?

C8 The apparatus below acts as a source of electrons. It is, however, a very special piece of apparatus. Electrons can only come out of it one at a time. Draw on the diagram below what you think happens to the electrons. Add any words of explanation on the diagram and/or in the space below.




C10 In some science textbooks, especially chemistry textbooks, when diagrams of atoms or molecules are drawn they do not show individual electrons in orbit but describe **electron orbitals** or **electron clouds**. Why is this?

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Title: ADVANCED LEVEL PHYSICS STUDENTS' CONCEPTIONS OF QUANTUM PHYSICS

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Corporate Source: PAPER PRESENTED AT THE SINGAPORE EDUCATIONAL RESEARCH ASSOCIATION CONFERENCE

Publication Date: 1995

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