Third Misconceptions Seminar Proceedings (1993)

Paper Title: What is the nature of the understanding of the concept of 'wave-particle duality' among pre-university Physics students?
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Keywords: concept formation,philosophy,research methodology,concept formation,misconceptions,constructivism,atomic theory,pilot project,data interpretation
General School Subject: earth science
Specific School Subject: quantum mechanics
Students: advanced

Macintosh File Name: Mashhadi - Physics
Release Date: 12-16-1993 C, 11-6-1994 I

Publisher: Misconceptions Trust
Publisher Location: Ithaca, NY
Volume Name: The Proceedings of the Third International Seminar on Misconceptions and Educational Strategies in Science and Mathematics
Publication Year: 1993
Conference Date: August 1-4, 1993
Contact Information (correct as of 12-23-2010):
Web: www.mlrg.org
Email: info@mlrg.org

A Correct Reference Format: Author, Paper Title in The Proceedings of the Third International Seminar on Misconceptions and Educational Strategies in Science and Mathematics, Misconceptions Trust: Ithaca, NY (1993).

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What is the nature of the understanding of the concept of 'wave-particle duality' among pre-university Physics students?

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Abstract
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 usually at the primary and lower secondary school level. However there has been comparatively little research on students' perceptions and understanding of quantum physics. A review of research, and a conceptual analysis of the underlying philosophical assumptions underlying the learning and teaching of quantum physics is presented. An interim report is presented on a new study to elicit students' conceptions of quantum phenomena.

1 INTRODUCTION

...nobody really understands quantum theory
Richard Feynmann

Particularly 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 physic significant research on *students' understanding* of such revolutionary phenomena is only beginning to emerge.

This new study is designed to build on and complement previous work carried out principally by research groups in Bremen, Berlin and València. The aim of the Students' Conceptions of Quantum Physics Project is to elicit students' conceptions of quantum phenomena, investigate their use of metaphors and analogies in constructing conceptual models, map their conceptual development over two years to 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.

2 'WAVE-PARTICLE DUALITY'

Elementary particles seem to be waves on Mondays, Wednesdays and Fridays, and particles on Tuesdays, Thursdays and Saturdays
Sir William Bragg

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. 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 yet 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).

3 GENERAL PHILOSOPHICAL CONSIDERATIONS

3.1 SHOULD QUANTUM PHYSICS BE TAUGHT AT THE PRE-UNIVERSITY LEVEL?

There are a number of interrelated and unresolved questions concerned with research and teaching in this area. For instance there is the curriculum issue, should Quantum Physics be taught at the pre-university level? As the 21st century rapidly approaches school physics is essentially quantitative Newtonian physics (i.e. 'classical physics'). 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 Osborne (1990) argues:

> Physics, as taught in schools, presents to children a selected subset of what we understand about the world. We need to question the premises of the choices that have fashioned the physics component of the present-day science curriculum.

3.2 WHAT SHOULD THE SYLLABUS CONTENT BE?

The question then arises: if quantum physics is taught, what should be taught? 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 is typified by that for the Associated Examining Board which involves:

> Section 6.2 Quantum Phenomena
> The characteristics of the photo-electric effect: the effect of frequency and intensity; threshold frequency; work function.
> (Simple experimental demonstration of the photoelectric effect is expected).
> Photons; the Planck constant, $E = hf$; the Einstein photo-electric equation.
> Line spectra: their sources, characteristic emission and absorption spectra.
> (Candidates are expected to know practical methods of demonstrating emission and absorption spectra in the laboratory).
> Transitions between energy levels; $E_1 - E_2 = hf$; energy level diagrams.
> Nature and sources of continuous and band spectra.
> Wave-particle duality of electromagnetic radiation.
> Candidates should appreciate that some phenomena [e.g. interference and diffraction] provide evidence for a wave model whilst others [e.g. the photo-electric effect] provide evidence for a particle model).

The syllabus does 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'.

In teaching physics the teacher is 'persuading' students to 'see' phenomena and experimental situations in particular ways, to start to wear the physicist's 'conceptual spectacles'. Karl Popper in *Conjectures and Refutations* (p. 47) states that "observation statements and statements of experimental results are always *interpretations* of the facts observed . . . they are interpretations in the light of theories". Holton (1972) expresses the ethical dilemma:

> All teaching requires one to anguish about honesty - even in a physics course one never tells the whole truth about physics.

Gil and Solbes (1993) analysed 42 Spanish physics textbooks, and concluded that between 83 and 95% of these did not refer to:

1. the non-linear character of the development of physics
2. the difficulties which originated the crisis of classical physics
3. the deep conceptual differences between classical and modern physics

A similar situation exists for the standard UK A-level textbooks (e.g. Duncan, Muncaster, Nelkon). Gil and Solbes (1993) also point out that between 68 to 79% of the texts they analysed:

> 1. interpret Einstein's $E = mc^2$ equation as an expression of mass/energy transformations
> 2. reduce the corpuscle/wave duality to only the undulatory or the corpuscular aspect
> 3. explain the quantum indetermination as a lack of precision of instruments or as a random consequence
> 4. give a simplistic view of elementary particles as ultimate 'bricks' of matter without internal structure.

What form of 'explanation' should be provided to students? The formalism of quantum mechanics has viable interpretations and corresponding ontological implications that are substantially different from the standard indeterministic/acausal Copenhagen interpretation (Cushing 1990). However the Copenhagen interpretation implicitly underlies descriptions and explanations provided by UK Advanced Level physics textbooks but is usually not made explicit. An A-level textbook would typically refer to 'wave-particle duality' in the following manner:

> ...What the reader must accept, though, is that the idea of light being a wave motion and the idea of it being a particle motion are merely two different models which help us explain the behaviour of light; neither is necessarily a literal description of what light is. . . The de Broglie waves, though often referred to as **matter waves**, are not composed of matter. The intensity of the wave at a point represents the probability of the associated particle being there.
> Muncaster (1993)

An explanation is provided by a successful formalism with a set of equations and rules for its application, such as non-relativistic quantum mechanics, including the Copenhagen interpretation. At this level the theory can be given an 'instrumentalist' interpretation. According to the Oxford English Dictionary, 'to explain' is 'to make intelligible or comprehensible by the intellect', while 'to understand it' is 'to grasp the idea of or to apprehend clearly the character or nature of', with 'to apprehend' meaning 'to lay hold of, to seize, to take possession of.' Cushing (1991) suggests that scientific theories function on three levels:

1. empirical adequacy, i.e. 'getting the numbers right' using a formula that reproduces the observed data
2. (formal) explanation
3. understanding

Mythical understanding (Eliade 1963) is a way of participating in the 'significant' world and dealing with its mystery. Religious understanding is symbolical and appeals to divine Being.

Philosophical understanding is 'essential' and claims the ultimate validity of its solutions. Scientific understanding is external, and based on the objectification of phenomena that are to be accounted for. Furthermore, scientific understanding is conceptual and postulates natural causes, forces , and functions. It is also hypothetical and exposed to empirical tests. Unlike everyday life understanding, scientific understanding is subjected to the rules of scientific methodology.

Cushing rightly separates explanation from understanding and argues that (formal) explanation is essentially what Salmon classifies as a covering-law explanation, as much of scientific explanation is just such formal explanation. It does not necessarily provide any sense of understanding. Salmon (1985) concedes that:

> It may turn out that the causal conception of scientific explanation has limited applicability. (p. 298)

There are cogent reasons for holding that explanation in quantum physics is not causal. Salmon views scientific understanding as being produced by explanations. He classifies three basic conceptions of explanation as the:

1. epistemic
2. ontic (which are essentially causal)
3 modal varieties (which are based on necessity)

For Salmon, scientific explanation is an answer to a why question. If this were accepted then a true explanation must produce understanding, and that causality (though not necessarily determinism) are essential features of genuine explanation. Salmon (1985) represents quantum theory as providing an epistemic explanation of empirical data and this he argues:

> ....constitutes strong evidence of the adequacy of the epistemic conception of scientific explanation (p. 299)

Achinstein (1985) discusses explanation by reference to understanding. For Achinstein 'understand' refers to comprehending the terms in a question (or answer), or 'making sense of' a statement. Achinstein's 'explain' depends upon the sense given to 'understand'. Achinstein's analysis of explanation and understanding stresses its pragmatic aspects, including contextual factors. van Frassen (1980) lays an emphasis on the pragmatism of explanation:

> Really [explanation] is a three-term relation, between theory, fact and context (p. 156)

At the microscopic level 'physical reality' cannot be directly perceived by the senses. As a consequence it is not intrinsically knowable (in the same sense) as macroscopic reality. It can however be approached at an inferential level using measurements from macroscopic instruments. Physical models based upon macroscopic experience suggest analogies. Mathematical models can be suggested by physical models (and vice-versa). These usually represent a further simplification for mathematical convenience.

A mathematical model can be associated with more than one physical interpretation. All models are subject to a 'natural selection' provided by internal consistency and by the experimental test of their inferences beyond the phenomena with which they were originally devised to exemplify. Kidd *et al* (1989) point out that Einstein's photoelectric equation is essentially a mathematical model that eliminates 'unnecessary' details about structure and extent of the radiation and focuses solely on energy transfer. As Harre (1961) has said concerning models:

> ...they carry the picture with which everyone, schoolboy, student, engineer and research worker, operates in dealing with problems in his field. You may deny that you have a model and be as positivistic as you like, but while the standard expressions continue to be used you cannot but have a picture.

The term ‘mental image’ is too vague to determine the nature of mental images. The term ‘mental image’ is usually used with regard to the internal representations involved in mental imagery. However, as Ned Block (1983) points out this has been used to refer to the *experiences* involved in imagery, also mental states that include these experiences and others, and even abstract ‘imaginary’ objects. In the 17th century ‘natural philosophers’ did not distinguish between heat, temperature, and even perceived temperature.

3.3 HOW SHOULD QUANTUM PHYSICS BE TAUGHT?

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 facts very easily after a short period of incubation, where doubt is allowed." Faucher (1987) 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.

At degree level in the UK the subject area is usually taught as a system of experimental and mathematical principles without much of an emphasis on its conceptual structure. Students are (certainly initially) expected to accept the rules at their face value, as they work extraordinarily well. however, by the time they do become proficient in their use they tend to forget the conceptual problems inherent in their character.

How should quantum physics at A-level be taught? The principal objective of physics teaching is that students learn concepts in a meaningful manner. Ausubel (1968) describes meaningful learning as occurring when a person consciously and explicitly links new knowledge to relevant concepts or propositions that they already have. Meaningful or deep learning provides confirmation that the student has been able to 'internalise' a new concept. The principal test that this has occurred being the ability to apply the new knowledge to other situations. In contrast, rote or surface learning occurs when the new knowledge is not systematically incorporated into the cognitive structure. The student may be able to recall the information but not able to apply it to novel situations. Ausubel (1968) asserted that:

> The most important factor influencing learning is what the learner already knows; ascertain this and teach him accordingly (p. iv).

However, Osborne and Freyburg (1985) have argued that this statement is ambiguous, and can be used to support different theories of learning. As Shayer and Adey (1981) point out a Piagetian interpretation would involve determining the stage of development of the student and then choosing curricular materials to match his/her level of development. An alternative interpretation would be to elicit the preconceptions of the physical world that the student brings to lessons and then design curricula to enable the student to change these conceptions so that they are more compatible with the accepted (teacher's) conceptions of the world (Osborne and Freyberg, 1985; Driver and Bell, 1986). Science education has been structured around what is perceived to be the scientist's concepts of the natural world. The *tabula rasa* conception of the learner has come to be replaced by many researchers with the concept of the learner who brings to the classroom a complicated body of personal knowledge and understanding (Ausubel, 1968; Pope and Gilbert, 1983; Driver, 1981; Erickson, 1979; Osborne and Gilbert, 1980). During lessons examples used to illustrate a concept may convey a totally different meaning to the student, the net result being that the actual outcome may well be different from the intended (Anderson, 1986).

Teaching involves the construction by the student of mental models for entities not perceived directly, e.g. light (quanta of light), electric current (electrons), particle of matter (atom). This modelling process is complex as it requires students to:

1. construct and use certain entities (these may be sets of objects or systems)
2. describe these entities in exact ways using certain parameters (e.g. mass, velocity, temperature change).
3. account for the processes of interaction between the parameters by describing relationships between them (using inventions such as force, heat, electric current).

Perhaps not surprisingly the building of such complex models requires considerable effort and time from the student.

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), 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.

The research group headed by Professor Niedderer, based at the University of Bremen in Germany, have implemented a teaching approach for grade 13 students (age 18-19) in upper secondary school based on the following principles (from Niedderer, Bethge and Cassens 1990):

> 1. From Bohr to Schrödinger: whereas most teachers at the moment teach Atomic Physics on the basis of Bohr's model, the Schrödinger model, within our more qualitative approach based on the notion of standing waves, allows for more and better explanations, especially in relation to chemistry, and is nearer to what scientists of today believe.
> 2. Reduce the mathematics involved in a Schrödinger approach. We use the analogy of standing waves to understand the basic concept of *state* ....in atoms, molecules and solids. We do not use analytic solutions of the Schrödinger equation; instead, we use the Schrödinger equation in a "semi-quantitative" way ....
> 3. Consider chemical applications, not only interpretation questions. We test our quantum model mainly by asking what macroscopic phenomena can be explained or predicted, unlike other teaching approaches where philosophical questions about, for example, the Heisenberg uncertainty relation are more central (c.f. Fischler, et al., 1989; Wiesner, 1989). We use classical analogies (e.g. standing waves) rather than stressing a "totally new type of thinking".

Fischler and Lichtfeldt (1992), based at the Free University of Berlin, advocate an approach to teaching quantum physics in which:

> (a) Reference to classical physics should be avoided.
> (b) The teaching unit should begin with electrons (not with photons when introducing the photoelectric effect).
> (c) The statistical interpretation of observed phenomena should be used and dualistic descriptions should be avoided.
> (d) The uncertainty relation of Heisenberg should be introduced at an early stage (formulated for ensembles of quantum objects).
> (e) In the treatment of the hydrogen atom, the model of Bohr should be avoided.

If the students' ideas are perceived to be in conflict with what is thought to be the 'right answer' as held by the researcher's perceptions of the scientific community they have been variously described as: students' conceptions, misconceptions, preconceptions, childrens' science, alternative conceptions, alternative frameworks. The label applied depends upon the researcher's own views of the nature of knowledge (Gilbert and Watts 1983). Such 'alternative conceptions' are often strongly held, very resistant to change and can impede further learning (White and Gunstone 1992). 'Surface learning' can result in students performing well in a test , yet not undergoing any meaningful change in their conceptions of a particular phenomena.

There are (ontological) assumptions concerning the nature of the social phenomena being investigated. Is social reality external to the individual or is it the result of individual consciousness? Is reality of an objective nature, or the result of individual cognition? The 'nominalist' view argues that objects of thought are merely words and that there is no independently accessible thing constituting the meaning of a word. The opposing 'realist' view holds that objects have an independent existence and are not dependent for it on the knower. Did J. J. Thomson discover or invent the electron?

There are also epistemological assumptions concerning the very bases of knowledge. Burrell and Morgan (1979) ask whether:

> 'it is possible to identify and communicate the nature of knowledge as being hard, real and capable of being transmitted in tangible form, or whether "knowledge" is of a softer, more subjective, spiritual or even transcendental kind, based on experience and insight of a unique and essentially personal nature. The epistemological assumptions in these instances determine extreme positions on the issues of whether knowledge is something which can be acquired on the one hand, or is something which has to be personally experienced on the other.'

The nature of the research study involves viewing 'knowledge' as personal, and subjective. Since the study is concerned with an understanding of the way in which the individual creates, modifies and interprets the concepts presented by the physics teacher the methodological approach adopted will involve both qualitative, and quantitative elements.

4 PREVIOUS RESEARCH

The most systematic and extensive research to date has been carried out by the Bremen and Berlin groups. Niedderer (1987) reported on Bormann's (1987) work on students' attempts to reconcile the wave-particle duality of electrons:

> (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), in Bremen, 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**
> 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), 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.

Appendix A provides a bibliography of research in this area.

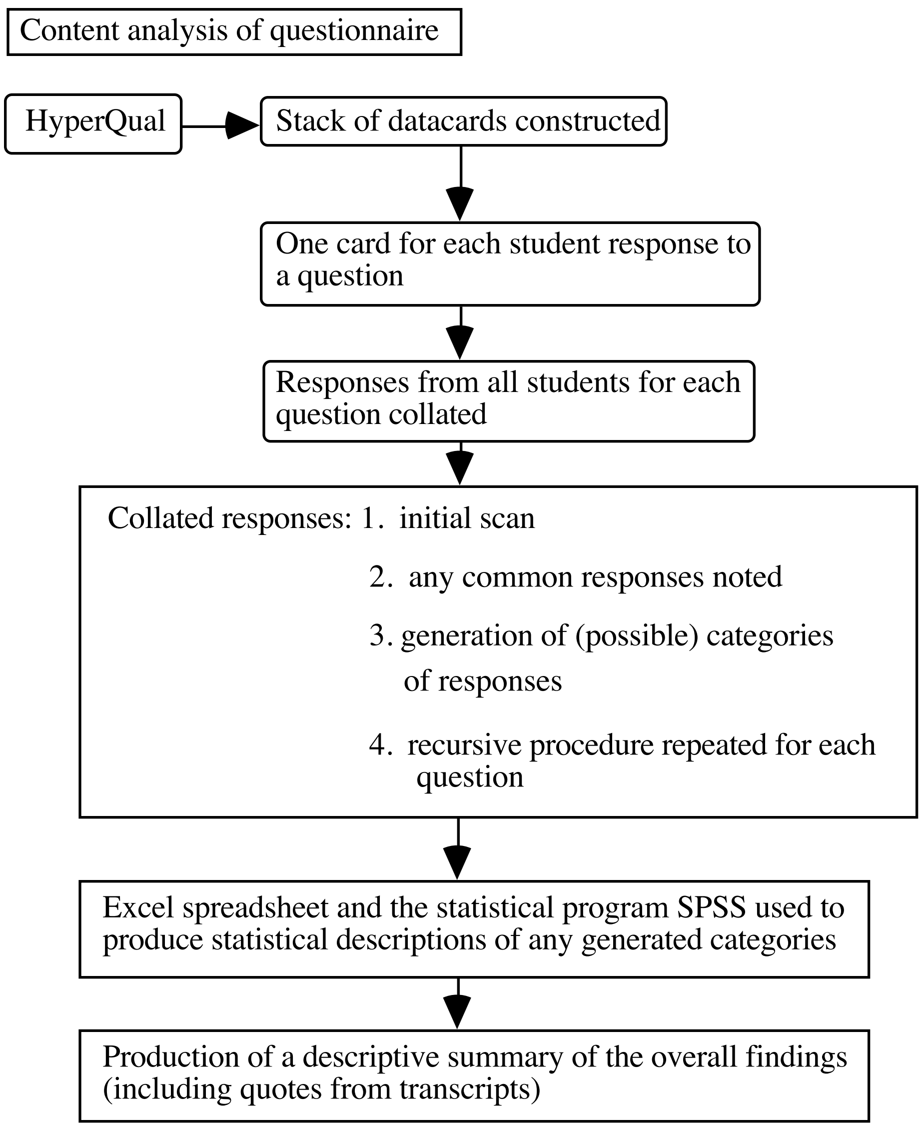
5 INTERIM REPORT

5.1 METHODOLOGY

This preliminary pilot 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. The principal aim was to trial some of the data-gathering, and analytical techniques. The second phase commences this October and consists of semi-structured questionnaires to all A-level

Physics students (and teachers) in Oxfordshire (N ~ 300), complemented by case studies of a small sample of students (N ~ 10). Research instrumentation will involve the use of classroom observation, concept mapping, semi-structured interviews, questionnaires, and the analysis of student-work. There will be pre- and post-teaching questionnaires over a two-year time period to monitor conceptual development.

The following interpretative methodology was adopted for the construction of meaning from the data:



5.2 IS REALITY UNCOVERED OR CONSTRUCTED?

Is reality of an objective nature, or the result of individual cognition? The ontological 'nominalist' view argues that objects of thought are merely words and that there is no independently accessible thing constituting the meaning of a word. The opposing 'realist' view holds that objects have an independent existence and are not dependent for it on the knower. The questionnaire (see *Appendix B,* Question C6) asked, was the electron invented or discovered?

A substantial majority of students (~80%) used the word 'discover' in the sense of 'un-cover', that is, unveiling or becoming aware of something that was there, fully formed, beforehand. Typical comments included:

> The electron was discovered. J.J.Thomson was not "God", the electron existed before he discovered it.
> Questionnaire 42/C6

> J.J.Thomson couldn't have invented the electron because it had always been there and therefore can only be discovered. Thomson could have however invented the concept of the electron being there which is what the student meant.
> Questionnaire 19/C6

Developments in the philosophy of science (c.f. Kuhn, Popper etc.) have had implications for the changing meanings associated with words such as 'observe', 'perceive', 'discover', 'theory' and 'facts'. As Sutton (1992) points out the meanings of words in science change over the years. There appears to be no clear conception that physics is a product of human beings, but rather an acceptance of the epistemology that scientific knowledge comes from 'things' rather than from people.

Sutton (1992) advocates emphasising the importance of developing ideas and testing ideas. and showing the provisional nature of theories by using 'as-if' phrasing:

> 'It is hard to know what "really" happens in this television tube but it is *as if* tiny charged particles were emitted from this part here....'

Most (~80%) of the students felt that there was more to 'understanding' than mathematical formulae. The following comment encapsulates the 'desire' of most of the students for a realist/physical understanding of a concept:

> ...there is obviously something physical happening which mathematics cannot explain fully, also, what is the point of using a formula you don't understand.
> 13/C7(g)

Only one-third of the students felt that 'physics consists of a set of facts which are always going to be true', and two-thirds felt that 'scientific models (e.g. the model of the atom) are not copies of reality '. However nearly two-thirds of students felt that 'physicists discover a theory because the idea was there all the time to be uncovered'. Overall the majority of students feel that 'science' is attempting to capture an external reality , through observation and experimentation, and is moving steadily closer to 'the truth'. Furthermore the physicist is not necessarily a 'completely disinterested, objective being' but is aided in his/her search for objectivity by 'formulas [which] give a description of nature that does not depend on the physicist's beliefs or opinions'.

5.3 HOW DO STUDENTS VIEW THE ATOM?

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

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

The **mechanistic** conception (held by ~ 25% 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 there are probably so many of them it would be very hard to draw.
> 3/C10
>
> 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
>
> Because nobody actually knows the position of an electron because they move around so fast, and they are very small.
> 27/C10

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 realising that there are limitations:

> I would prefer it to be stressed more that all atomic models have faults, but some people find it hard to imagine something without visualising it.
> 33/C5(c)

> 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 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%) 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%) 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

> Because electrons are not confined to one particular straight line, the(y) move randomly between a minimum and maximum position in an orbital/cloud around the nucleus.
> 47/C10

> Because it is said that it is an electron cloud which is around a nucleus but, it is actually electrons at different energy levels, pass over the whole nucleus. It is shown in this way because it is too difficult to show the different levels easily as on paper it is in 2D and not 3D.
> 54/C10

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

> Its useful in that it shows an electron orbits and isn't stuck onto a nucleus but its also misleading in that electrons cannot be pinpointed they are in fact smeared charge clouds totally surrounding the atom.
> 29/C5(c)

> 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

> This sort of diagram *[electron in circular orbit]* is misleading, as electrons don't travel round as particles. Electrons for[m] electron charge clouds, which completely surround the nucleus. The diagram shows the atom as only 2-dimensional.
> 27/C5(c)

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

> Maybe the student was stupid and couldn't believe that something so unimaginable exists. Or maybe he was clever and believed that when there are so many contradictory things about electrons, it is hard to define one.
> 33/C6

> The electron is not a little ball orbiting another ball, but *it is something hard to imagine, and possibly best not imagined at all.[present writer's emphasis].*
> 33/C10

> ...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)

5.4 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 *Appendix B*, 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)
>
> Nonsense - if electrons interfere, they would jump out of orbit so no atoms would exist.
> 22/C7(c)
>
> Its not totally unreasonable but I think it may be possible that no diffraction is occurring but that some electrons are being stopped by the atoms in the graphite and the regular pattern is due to the regular structure of graphite. The pattern is then formed by the electrons that get through and can be deflected by a magnet.
> 37/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

> They move through the gap and make a dot on the screen. Straight from the source in a straight line to the screen.
> 18/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:

> Superposition. Minima - electrons interfere destructively. Maxima - electrons interfere constructively.
> 14/C7(d)

> 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)

> The electrons are diffracted in the same way as light through a slit.
> 22/C8

> Again as in Youngs slit through the slit the electrons would disperse and when their paths cross, destructive or constructive interference will occur. Because its only one slit the fundamental band in the middle of the fringes will be brighter and much wider than others will be about half the width and half brightness which will continue to fall away with distance from centre, as energy disperses.
> 29/C8

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%) 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)

> ...The probability waves are interfering and when the wave strikes the flourescent screen it can be observed as an glow caused by an electron.
> 55/C7(d)

Another minority viewpoint regarded electrons as consisting of **'smeared charge'**:

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

That they are arranged in shells and are not discrete - they form "cloud rings" around a nucleus.
22/C7(a)

A very small number of students (~ 4%) 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)

I think that physics is merely subjective, and the aim is to determine how to make use of nature. If the behaviour of the electrons cannot be determined, it is pointless "making something up", since it serves no purpose. The behaviour of the electrons does not exist, and any metaphysical approach is wrong, since it has no apparent effect on the universe.
42/C7(g)

6 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. However, further work needs to be carried out using a larger database to establish the generalizability of any findings, and more focused research on the use of language (e.g. metaphors and analogies) and the micro-processes involved in cognitive adaptation.

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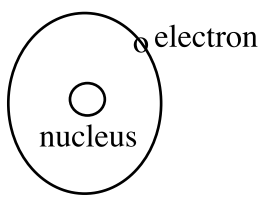
<u>Appendix B</u>

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.



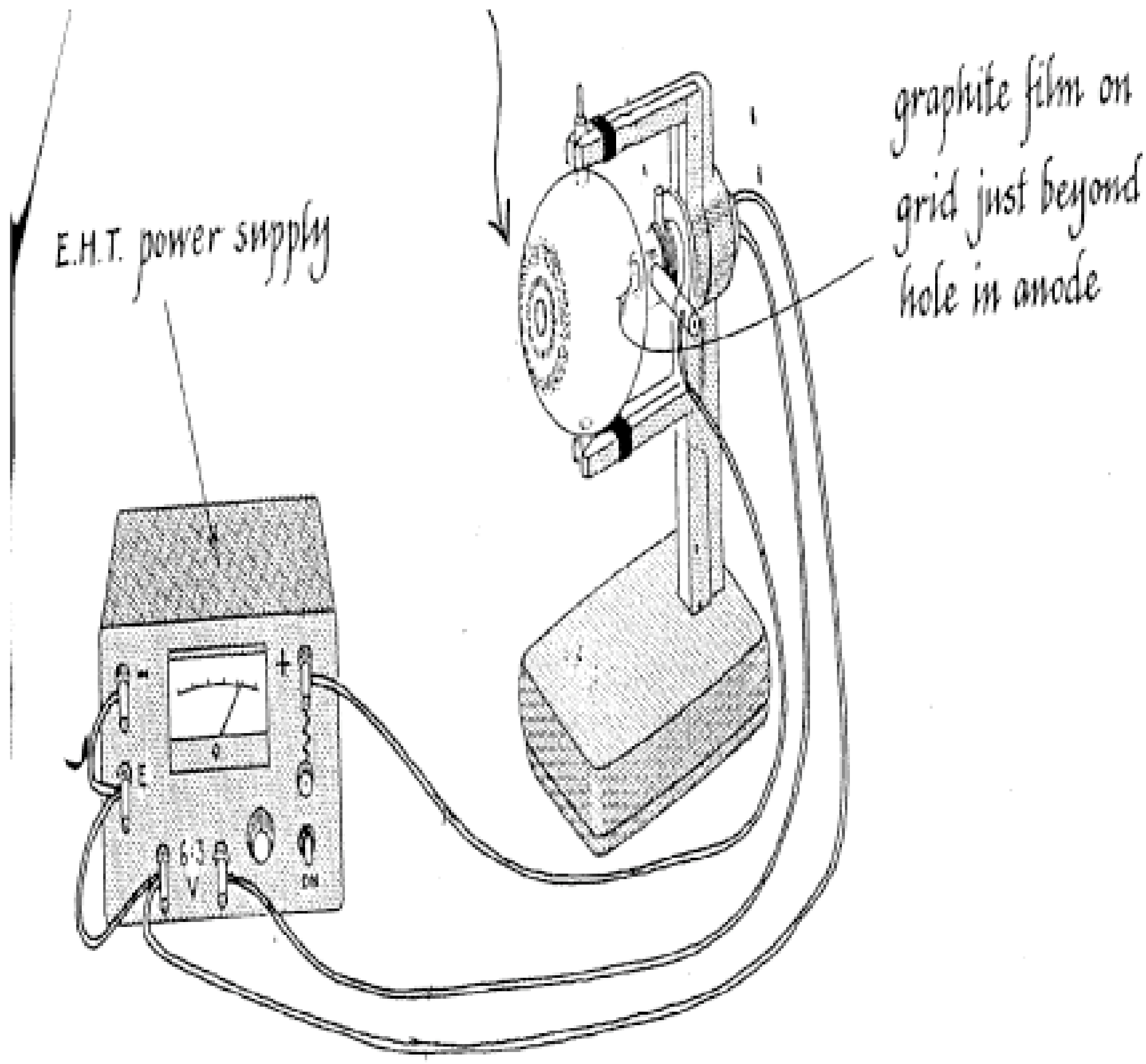
(b) What do you think lies between the nucleus of an atom and its electrons?

(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."

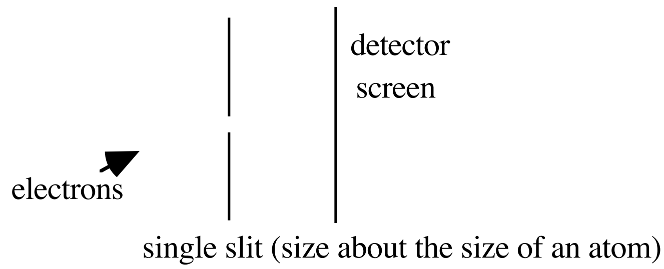
Why should he say this? Do you agree with him?

(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?