A Study of Norwegian Upper Secondary Physics Specialists' Conception of Atomic Models and the Wave Particle Duality.

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by

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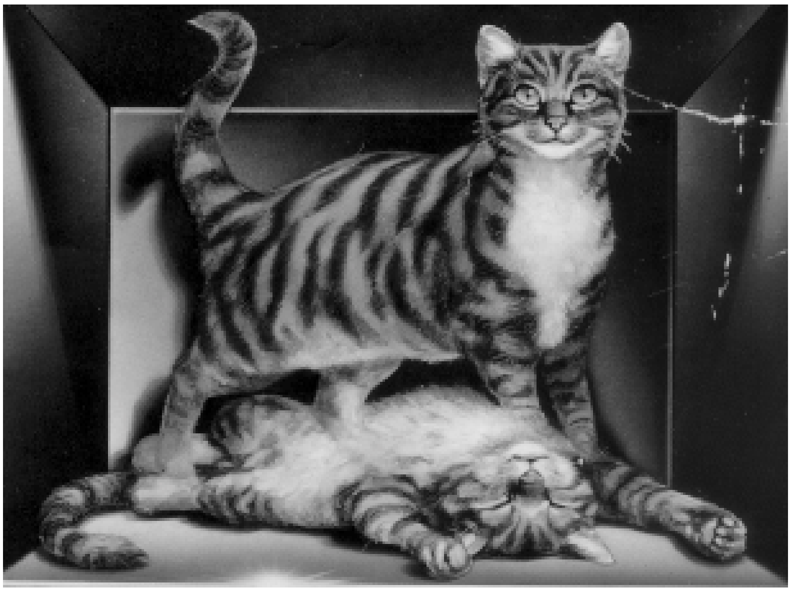
Abstract

The study reported in this talk is a survey (n=236) that examines how upper secondary students in Norway (18-19 years old) come to terms with the main idea of quantum physics as contrasted to classical mechanics. Two concepts were chosen as indicators, the concept of modelling the atom and the concept of wave-particle duality. The main conclusion is that most students seems to be locked into the classical worldview where material particles have definite locations and moves along definite tracks. Very few of the students demonstrates, through the items given, that they have been able to grasp that, on this scale, the phenomena can not be understood through the lenses of classical mechanics. This paper goes into details on the part of the study concerning atomic models, but only summarises the part on wave-particle duality. A paper to be published in the Int. J. of Sci. Edu. presents this latter part in more detail (Olsen, in press).



(The picture is taken from the cover of the book "In Search of Schrödingers Cat", by John Gribbin)

Background and aim of study

The Norwegian physics courses in upper secondary school have, since the early seventies, included what is often called modern physics. This means that students are introduced into X-rays and the photoelectric effect and simple models for understanding these phenomena. When discussing these phenomena a model of the atom is implicitly used, but not discussed in any depth. Finally the wave-particle duality is introduced through a brief description of the double-slit experiment for electrons. In many standard textbooks on modern physics used in introductory university studies, a historical mode of explanation is used. What could be asked, though, is whether this approach induces a genuine understanding of how strange these phenomena are when perceived through the lenses of classical physics, and how different quantum physics is from the classical paradigm.

We have today a complex knowledge of student thinking characterised by widely held alternative conceptions in all fields of science (Fraser and Tobin 1998). The area of modern physics was mentioned by Duit (Pfundt and Duit 1994) as an example of a field that did not receive a lot of attention, but in the years since then there have been an increasing interest in this field of research. This research could in general terms be summarised as showing that students' conceptions in quantum physics do not lead to a major restructuring of their already existing knowledge (Niedderer et al 1990, Fischler and Lichtfeldt 1992a and b, Mashhadi and Woolnough 1996, Johnston et al 1998, Petri and Niedderer 1998, Ireson 2000). The studies mentioned cover a wide range of countries and students at both pre-university and university level receiving different types of instruction.

The purpose of the study presented in this paper is to supplement these studies by describing which atomic models the students prefer, and how skilled they are in discussing the pros and cons of the simple orbital model (part 1). In the second part of this paper I give a short summary of the study of students understanding of wave-particle duality. How do they make meaning of this rather abstract and difficult concept?

The purpose is not to discuss quantum mechanics per se, but I will in the end argue that educational research into students subject matter knowledge and thinking should take care to include specific features of the subject in the analysis of student responses, and more importantly, when suggesting possible implications for teaching.

Methods and samples

The study presented was performed shortly after the students had finished their lessons on quantum physics (spring 1999) as part of their ordinary physics course. No intervention on the teaching was made. It is to expected that Norwegian physics teachers follow a somewhat similar approach because there are some strong driving forces towards conformity in our school system. These forces are a centrally developed and written curriculum, a centrally developed written exam and a very small selection of available textbooks (three different textbooks exist). However there were rather large differences in the instruction in these classes. For instance; the length of instructional time students had received varied greatly from 4 lessons to 20 lessons.

A total of 236 students participated from 20 different schools randomly chosen. In my presentation only descriptive statistics will be given, that is the relative distribution of students' answers. The participating students answered a written questionnaire with several items covering different parts of the quantum physics curriculum, not only questions on atomic models and the wave-particle duality as will be presented in the talk. A complete presentation of the whole study exists in Norwegian (Olsen 1999a and b).

Part 1: Students' understanding of atomic models

Short review of previous research

In the following I will present some of the studies mentioned above in more detail. Fischler and Lichtfeldt (1992a) performed a study with an experimental design. The control group had been introduced to quantum physics through a course that resembles the Norwegian as described above, while the experimental group received instruction focusing on an atomic model explaining their stability through the concept of localisation-energy, a concept based on Heisenberg's uncertainty relation. The control group explained the stability of atoms by reference to the centrifugal force being balanced by the attractive electric force between the electron and the nucleus. Also some of the students explained the stability by charges always repelling each other. Furthermore, some students had a vision of fixed shells that kept the electrons in place. Another German group, in Bremen, have over an extended period of time worked on the teaching and learning of quantum mechanics. This group has developed a unique theoretical approach with its own terminology to characterise students learning processes in order to be able to study pathways in learning (Niedderer and Schecker 1992, Petri and Niedderer 1998). They have developed their own course focusing on the physics of atoms (Niedderer et. al. 1990, 1998 and 1999) and they have performed studies on how students come to terms with the concept of atoms. In a case study Petri and Niedderer (1998) describes how one students' conception of the atom is changed by instruction. The students' initial model is a simple orbital model of the atom, but gradually he learns to apply more sophisticated models, such as an electron cloud model to explain phenomena. By the end of the instruction they conclude that the student uses several models dependent on the context and situation. The strongest model however, the model he always comes back to, is the simple orbital model. Other studies also clearly documents that students are very much attracted by a simple orbital model (Mashhadi 1995, Müller and Wiesner 1999, and Unal and Zollman 1999). I believe that Fischler (1999) is in his right when stating that:

> *Students who have been shown the efficiency of Bohrs atomic model will have little success in surmounting this illustrative model. To resort temporarily to mechanical aids for the sake of illustration would be to conceal the fundamental difference between the students' concepts encouraged by this model and the correct physical description. An electron's orbit is not simply an auxiliary device which is almost correct and can thus function for a while as a comprehensive aid. Every single argument supported by the concept of orbit makes the necessary change in thinking*

> *more difficult, delays the due process of discarding mechanical models, and finally renders this process impossible.*
> (p. 33)

In the Norwegian physics (and chemistry) courses we return to the simple orbital model several times, when explaining chemical reactions, the photoelectric effect, light emission, X-rays etc.

Results

There were two cognitive items focusing on students' conceptions of atomic models. The first item challenged the students to discuss the analogy between the atom and the solar system:

> Read the following statement: "The way the atom is built can be compared to the way the solar system is like". Discuss this statement.

Description	%
Simple analogy	41
Simple analogy + simple nonanalogical properties	29
Simple analogy + prob-lematic nonanalogical proposition	20
Non-response	10

- Planets have elliptical orbits
- Electrons can jump between orbits
- More electrons in one orbit
- Scale different
- Name of force different

- No defined orbit
- Only probabilities for different positions
- Choosing which model to use dependent on question

Figure 1: Distribution of responses to item "atom vs solar system" and some exemplars for answers in two of the categories used.

The answers where analysed by transcribing and repeated reading. The categories eventually used where a result of this repeated interpretative process. It is not established whether other would agree on these categories.

As can be seen from the table in the figure above, 70% of the student did not mention any serious "flaws" or problems with this analogy. They focused almost only on the analogical features in the comparison. The students mentioning some simple non-analogical features did not mention examples that could be characterised as approaching a quantum mechanical model of the atom. Furthermore they did not discuss explicitly that this analogy was just one out of many models to choose from, dependent on question asked.

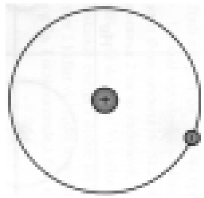
I another item the focus was on how the students preferred to visualise the atom when confronted with some examples with figures and describing text (the item continues on the next page:

Below are some descriptions (with figures) of how we can imagine a hydrogen atom

Which one of these fits best with how you imagine a H-atom to be?

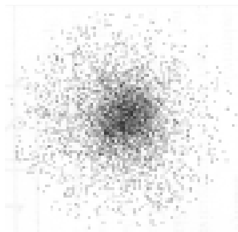
Circle one letter only.

A. The electron revolves the nucleus in a definite orbit with high speed

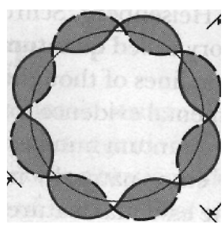


B. It is not possible to determine the position of the electron at one instant. Therefore it is impossible to visualise

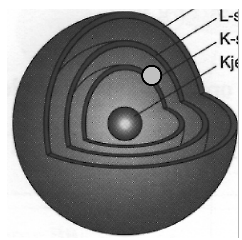
C. The position of the electron at one instant is best visualised by an electron cloud



D. The electron revolves the nucleus along a wave-shaped trajectory



E. Surrounding the nucleus are several electron shells in which the electron can be. When an atom is in the ground state the electron is located in the inner shell



F. The electron follows an orbit with a plane that shifts all the time.

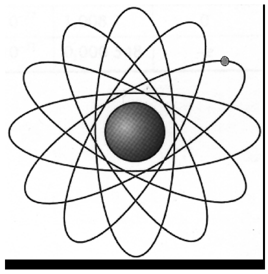


Figure 2: Item "Visualising the atom"

	Description	**%**
A	Simple orbital model	3
B	No visualisation	9
C	Electron cloud	37
D	"Wave-shaped" trajectory	1
E	Shell-modell	31
F	Rotating orbital	16
	Nonresponse	4

Table 1: Distribution of responses to item "Visualising the atom"

When reading the item carefully it can be seen that this is a special kind of multiple-choice question. Intentionally the student is asked to choose the model that fits best with his/her own imagination. The question is not to choose the correct alternative. By asking this way the intention is that the student must evaluate all the alternatives in order to reach an answer. Furthermore, the hope is that they perceive the difference between *correctness* on the one hand, and *preference* on the other.

Table 1 shows that the largest group of students prefer the electron cloud model. This group was dominated by students who used the only textbook that explicitly treated this model. Moreover, more than half of the students preferred models illustrating orbitals (or shells) of some kind. However, very few students chose the simple orbital model in alternative A. In comparison, most other studies, as referred to in the previous section, report that most students seem to conceptualise the atom through a simple orbital model. However, the question asked, and the research design, is not comparable to each other. Changing the item, and the method used to collect data, will obviously effect the responses from the students. For instance Petri and Niedderer (1998) asked students to *draw* the atom in their study. The easiest way to draw an atom is clearly an orbital model, which I believe explains why the simple orbital model was very common in this study. In the multiple-choice item presented above, the drawings are already made, which makes it easier to chose for instance a cloud model. Another finding, which differs from the other studies, is the fact that almost 40% of the Norwegian students seem to prefer the electron cloud model. On the other hand very few students gave reference to such a model in the open ended item. Also, in the other studies mentioned, very few reported that students applied the electron cloud model. These discrepancies clearly document how much the question asked effects the response given.

Students' responses on both items were also compared to see whether there were consistencies in the answers given. This revealed that 40% of the students answered both items in a consistent manner. This is in accordance with Petri and Niedderer (1998) who found that students where able to apply several models dependent on context and situation. Furthermore this is in accordance with my discussion above that different items have different foci and therefore triggers different models to be applied.

Conclusions and implications for teaching

As discussed above, a detailed comparison with other studies is not feasible. However, the responses given to the two items presented is in accordance with the main conclusion in all the other studies; that many students have a concept of the atom very much in accordance with a classical view. The electron is a particle, and it is possible to locate it within an orbital trajectory.

This should not come as a surprise for those of us who are familiar with the traditional way to introduce quantum physics. As mentioned earlier, a historical approach is often used in introductory material, both in upper secondary and at universities. This is a rather acceptable approach when considering how the physics developed in this period of time (1900 – 1930) is used by historians, sociologists and philosophers of science to demonstrate how knowledge in general is produced, and in the end, accepted by the scientific community. If this more general aim is the curricular focus a historical approach can be a good approach, and indeed there have been developed interesting units for instance on the story of the so called N-rays, claimed to be observed by Blondlot at the beginning of the 20^{th} century (Burdett, 1989), and on the debate on the wave-particle duality in the same period (van der Valk, 1989). Also, we tend to like a good story. And the story of the development of quantum physics is one of the very best stories to be told from the history of physics, as documented by the numerous biographies and popular books describing the persons and the tremendously brave thoughts that were put forth. The narrative form is a way to get personally connected to these thoughts, the persons and the science society involved.

However the historical approach as used in most standard textbooks, both Norwegian and English texts, could be said to be quasi-historical. By this I mean that the approach gives a simplistic view of the actual historical process, it is presented in a linear fashion where knowledge is gradually discovered by careful observation of the phenomena involved, and very often the persons in the centre of the story are presented very iconic, promoting the myths of the genius and almost God-like scientists. The latter fact is enhanced when students occasionally can read about Einstein, Bohr etc. in newspapers or other daily life media. One illustrating example is Einstein’s explanation of the photoelectric effect. He delivered this in a paper in 1905. This is presented as a major break-through in the history of physics. This paper can be regarded as the first indication of how phenomena observed in daily life could be explained by using a different set of rules on the scale of atoms, that is, the quantum mechanical toolkit. The true story is however much longer, involves many more persons, and it involves the fact that this article was mainly ignored for two decades by other scientists at that time, among them Niels Bohr. Fischler and Lichtfeld (1992b) also recommend to abandon a historical approach, albeit of somewhat different reasons:

> *Central to the criticism is the reproach that in being oriented at historical development the teaching clings too much to conceptions of classical physics. The usage of mechanical models which is implied by this, unnecessarily sets up an additional obstacle for the appropriate understanding of quantum physics.*
> (p. 240)

Or as Sir Neville Mott said already in 1964, when describing the new Nuffield-curricula:

> *The Bohr orbits are now of only historical importance - though their historical importance is great. I doubt whether pupils ought to learn about them until they can get some inkling of what has replaced them.*
> (p. 408-409)

It is however in my view difficult to omit the simple orbital model completely. It is a good model when explaining some of the phenomena central in our courses. And no doubt will student still be introduced to octet-rules, relying heavily on visual orbital models, to explain simple chemical reactions in their chemistry or general science courses. What has to be at the very center all the time when teaching, especially when teaching about a world that cannot be seen, is that we operate on models of the world. These models are purposeful, they guide our thinking and they help us understand. But they are not pictures of reality. In my view, this has to be more explicitly treated. When we treat subjects from the world that can be seen with our eyes, it is easier for students to implicitly understand that we simply are working with a model in mind, for instance a schematic model of how blood circulates in our bodies. This is however not the case when talking about atoms. The students have no sensory daily life experience to help inducing that this is “only” a model.

When introducing quantum mechanics we also have to take care to be aware of some of the specific features of this theory. Some of the characteristics are listed below

- Entities exists / are measured in discrete quantities
- Non-intuitive (principal uncertainty, non-causality, non-locality, …)
- Mathematically formulated

- Qualitative interpretations embedded in everyday language which is rooted in classical mechanics
- Different interpretations coexist
- Mysterious, shocking consequences, incomprehensible?

Without going into details I will discuss how the actual subject involved should be taken into consideration when reflecting on consequences for teaching. First of all, in quantum physics itself, there are no great problems of understanding involved. It is a very powerful mathematical tool. Using this mathematical framework when describing phenomena on the atomic scale, is fairly straightforward, once you have learned the mathematics involved. However, when communicating this to the lay person, or potential physicists as in our physics classes, we are forced into making meaning from another toolkit, the ordinary life language. It is evident that when talking about quantum physics in this language, we are forced to use mechanical models. Niels Bohr once put this very well when saying that “truth and clarity are complementary entities.”

When communicating to the potential scientists in voluntarily selected courses our aim must be to tell the story of how different the world on the atomic scale behaves. We have to try to give a meaningful content in what the consequences of quantisation is, what the meaning of principal uncertainty is, and develop models that uses these features on the one hand, and are meaningful for the student at the other hand. The student should also be able to understand and communicate some of the major differences between classical and quantum mechanics. How this can be achieved? Well that is the challenge. What I hopefully have documented is that the traditional approach, relying heavily on semi-classical models from the early period of the development of quantum physics, is not suited to achieve the aims above.

Part 2: Wave particle duality (a short summary).

I would like to refer to an article in Int. J. of Sci. Edu. for a more detailed account of this part of the study (Olsen in press).

The students answered two almost identical multiple-choice (MC) itmes concerning the dual nature of both light and electrons (se Results). The students were also told to explain their answers in a following open-ended (OE) item. The answers on the OE – items were analysed along two dimensions. First they were categorised according to the students’ conception of the nature of the duality. Three groups of answers were formed (particle, wave and dual view) with ten subcategories describing the nature of their conception in more detail. Students’ answers on the OE– items were contrasted with their choice on the corresponding MC – item. Furthermore, categories were formed that ordered the answers according to their explanatory element (reference to phenomena, reference to types of waves / particles, reference to a defining property of a wave / particle)

Results

	Evaluate the statement below by circling the one you think is correct	*Distribution of responses (%)*	
		L	**E**
A.	**L**ight/**E**lectrons are both waves and particles	77	36
B.	**L**ight/**E**lectrons are particles.	2	59
C.	**L**ight/**E**lectrons are either waves or particles	5	4
D.	**L**ight/**E**lectrons are waves	9	0
E.	**L**ight/**E**lectrons are neither waves nor particles	8	1
Explain your choice:			

Table 1: Presentation of the item and results on the multiple choice question (L=light and E=electrons).

Students' responses on these two items clearly show that most students do not conceive of light and electrons as having a similar undulatory nature. Electrons seem to be conceptualised as particles and light seems to be perceived as having a dual nature.

The analysis of the OE – items support the findings from the MC – items that students conceive of the nature of electrons to be particle-like and light to have a dual nature. On the other hand, the answers to the OE – items give additional information on what they mean when using words as 'particles', 'waves' and 'dual nature'. Some findings can be highlighted:

a) Most students arguing that light have a dual nature were not able to give answers that explicitly addressed the nature of this dualism.

b) A small, but interesting group of students interpreted the duality as particles moving along sinusoidal trajectories.

Analysis of the elements used by the students to explain their choice shows that:

a) Reference to phenomena (e.g. interference) is commonly made to explain the dual nature of light.

b) Reference to a defining property (e.g. mass) is commonly made to explain the particle like nature of electrons.

Conclusions and implications

Despite that textbooks used by these students treat the nature of light and electrons as being equivalent, that is they have a nature of being both waves and particles at the same time, the students do not seem to accept this. They hold on to a particle view for electrons. Furthermore, the study shows that the concept of wave-particle duality is difficult to comprehend. Most students choosing a dual view in the MC – items, only give vague explanations in the OE – items, indicating that this concept is only loosely integrated with, and contrasted to, the classical concepts of waves and particles. These vague answers could be characterised as formulations without reference to any meaningful conceptual object. One important aspect of understanding is to make concepts intelligible, or to be aware of the basic qualitative ideas in which the facts and formulas are embedded as Duit and Treagust (1995) have stated. The students referring to particles moving along a wavelike trajectory demonstrates that they actually have made the concept of wave-particle duality intelligible, but this is done by a complete integration with the classical particle view.

Quantum physics is one of the greatest intellectual achievements of mankind. It fundamentally challenges both a classical and a common sense view on how the world in the atomic realm really is. This study shows that the concept of wave-particle duality does not introduce such a challenge for the students, or as Jones (1991) formulates it: *One thing is certain: To provide our students with the symmetric concept that the electron is sometimes a wave and sometimes a particle does not introduce any new concepts, and indeed closes off the road to new concepts*.

Some alternatives? (1)

- Use the Heisenberg uncertainty principle for what it is worth
  - Simple mathematics
  - Wide range of interesting applications
    - Stability of atoms
    - Virtual particles carrying forces
    - Vacuum energy
    - Fusions within stars
    - Radioactivity
    - Tunneling
    - ......
  - Gives attention to the principal uncertainty.

Some alternatives? (2)

- Dear to be mathematical
  - The ”IoP-Shaping the Future” – approach
    - When mathematics is necessary to understand the physics we should apply mathematics
  - Niedderer and Deylitz (1998)
    - Course material applying graphical software package to solve Schrodinger equation. ”Qualitative mathematics”

Some alternatives? (3)

- Using hands-on
  - Working on semi-conductor components, such as light diodes
    - Dean Zollman (1998) http://www.phys.ksu.edu/perg/papers/vqm/HandsOnQM.html
    - Lawrence (1996)
- Using virtual tools
  - Quantum mechanical experiments difficult to do with standard equipment in schools
  - http://www.colorado.edu/physics/2000/index.pl
- Less is more
  - Better to use 10 lectures on photoelectric effect

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