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The quantum atomic model 'Electronium': a successful teaching tool

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Abstract
This is the second of two papers focusing on the quantum atomic model 'Electronium'. The 'Bremen teaching approach', in which this model is used, is outlined and an analysis of the learning of two students as they progress through the teaching unit is presented. Finally an argument is presented to support the assertion that the Electronium model can be considered to be a successful teaching tool.

Introduction

The 'Electronium' quantum atomic model (Herrmann 2000) was first developed to address students' learning difficulties and alternative conceptions in this area of physics (see the preceding article, Budde *et al* 2002). In using the Electronium model as a part of the Bremen teaching approach, a number of *teaching hypotheses* were developed. Teaching hypotheses allow us to predict which taught content may support or inhibit students' learning, taking into account the students' preconceptions. The hypotheses are discussed in this paper by focusing on the learning of two specific students and relating this to what was taught. The findings for these two students are presented in short case studies and are related to the results of a wider evaluation project (Niedderer and Deylitz 1999) and also to the findings of other studies, to judge how representative these cases are.

The 'Bremen teaching approach'

In the Bremen research-based teaching approach (Niedderer *et al* 1997) the visual Electronium model is presented in addition to the probability model (a comparison of 'probability' and 'Electronium' models is set out in table 1 of the preceding article). Atoms are described from a quantum-mechanical perspective from the beginning, instead of introducing simpler but more limited models like the Bohr model. In order to support retention of student learning of the new models, they are applied to interpreting a variety of phenomena, including chemical bonds, charge density measurements, the size of atoms, spectra and the Franck–Hertz experiment. The current version of the teaching approach is available as a textbook for students (in English (Niedderer and Deylitz 1998) and German) and can be downloaded from the webpage: http://didaktik.physik.uni-bremen.de/niedderer/projects/quanten/index.html#dow

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The design of the study

The case study data, which are presented here, were collected as part of a project to evaluate the Bremen teaching approach (Niedderer and Deylitz 1999), in which three classes (26 students in total) were investigated. Alongside an evaluation of the learning of the full cohort of students, case studies, focusing on two 18-year-old students (Thomas and Klaus), were carried out to obtain a better understanding of the influence of the teaching on the development of the individual students' conceptions. Although it is not compulsory to study physics in upper secondary school in Germany, the choice of subjects is restricted and Thomas, especially, emphasized that he was forced to choose physics. Both students were about average in their school achievement in physics.

The data collected consisted mainly of audio-tape records of the regular school lessons (five lessons of 45 minutes per week, for approximately 18 weeks). In addition, Thomas attended private lessons (approximately 50 lessons), which were also audio-recorded. Before and directly after instruction the students provided written responses to questions probing their views and understanding of atomic models. To investigate the longer-term stability of the students' conceptions, control interviews were also held two years after the end of the instruction.

Initial teaching hypotheses for the Electronium model

Implicit in the approach to teaching the Electronium model were a number of teaching hypotheses that were developed from an analysis of previous research in various domains including quantum atomic physics (see the preceding paper). These hypotheses can only predict the *potential* construction of conceptions since learning is seen as a developmental process involving the cognitive system of a student, which is influenced but not determined by the teaching (Niedderer 2001).

The following are the three initial teaching hypotheses for the Electronium model.

Teaching hypothesis 1: Liquid–continuous. An analogy between Electronium and liquids may support the development of a conception of Electronium as being continuous rather than particulate in nature.

Teaching hypothesis 2: Movement of the electrons. A view of Electronium as being continuous in nature may support the development of conceptions of atoms in which electrons are not moving if they are in stationary states.

Teaching hypothesis 3: Acceptance of the Electronium conception by students. The visual appearance of the Electronium as a substance may support its acceptance by students.

Approach to analysing the students' learning

By carefully following the talk of individual students and relating it to the teaching content, it is possible to test these teaching hypotheses. Observations are made to ascertain whether, and after how many repetitions and discussions, the students construct the intended conceptions. In this way, the opportunities and difficulties presented by different teaching approaches can be evaluated against each other, and principled decisions about the planning and design of teaching can be made. Such an approach contrasts with more common practices in designing teaching approaches, which often involve following traditional teaching paths or relying on thoughtful, educated guesswork.

A mode of data analysis was developed which considers the influences of both the individual student's preconceptions and the taught content on the learning of the student. This approach is summarized diagrammatically (see figure 1 below) in such a way that differences between the contents that are taught (on the left-hand side) and the conceptions that the students construct (on the right-hand side) are made explicit. The influence of the taught contents on each student's conceptions is described in terms of the concept of 'resonance' (Budde 2001). The term 'resonance' is used to signal the fact that learning outcomes depend on the extent of 'fit' between the taught contents and the preconceptions of the student (von Glasersfeld 1992).

Results and conclusions

In the following section a summary of the findings relating to the two students is presented and this is linked to findings concerning other students.

Liquid–continuous

The teaching of 'Electronium as a kind of liquid' can be considered to be successful, in that it produced a congruent resonance (that means the student's conception is equivalent to the taught content) for both students. Thus, during lessons Klaus spontaneously referred to Electronium as 'a liquid-like state', whilst Thomas thought that Electronium was 'like a puddle of oil'.

The notion of 'Electronium as being continuous in nature' also generated a congruent resonance, but not to the extent anticipated.

For example, Klaus had two different conceptions. On the one hand he thought that the extended electron consisted of smaller subparticles, and his belief that Electronium is a kind of liquid acted to support this subparticle conception. Thus, in the interview immediately after instruction he commented:

> 'I think we have to assume that the electron consists of very small particles (...) because it is a liquid and a liquid consists of particles.'

However, in the control interview two years later, he stated that for an atom with five electrons 'there are no spaces between the electrons', which is interpreted as being a conception of a continuous Electronium. It is therefore concluded that exposure to the particle model of matter, possibly in previous physics lessons, resulted in the coexistence of the conceptions about liquids as being 'continuous' and consisting of 'particles' for Klaus and this led to his dual views on the nature of Electronium.

A further aspect of the continuous nature of Electronium is related to the interpretation of the absolute square of the Ψ-function multiplied by the entire charge as a continuous charge density. In relation to the concept 'density', Thomas had no conception of a mathematical density of continuous distributions in terms of mass or charge per unit volume. Therefore the conception of a continuous charge density is problematic for Thomas. He had an intuitive conception of density, in which the density is connected to discrete objects (e.g. atoms) in a certain area: the closer the objects, the higher the density. Fischler and Peuckert (1997) and Minstrell (2001) also observed this naïve distance conception. Thomas responded to the question, 'What is the meaning of density?':

> 'The atoms are more closely arranged.'

It is therefore concluded that because of the restricted explanation of density with the particle model, which was taught in previous physics lessons, the student is not capable of imagining a continuous mass or charge density. Hence, the student's conception of a discrete mass density is seen as a learning obstacle for the construction of the conception of Electronium as being continuous. On the other hand Thomas is able to imagine a continuous density of Electronium as being related to colour instead of charge or mass. He believes that Electronium is black where the density is high, and decreasing density means, for him, that Electronium turns to grey. This conception is highly influenced by the illustrations of atoms used and is not intended, but it is considered to be useful as an anchor for the teaching of a continuous mass or charge density.

Movement of the electron

Even if the Electronium was seen as consisting of smaller subparticles this did not influence the students' belief that the electron is not moving in the atom. Both students emphasized that the electron is not moving in the Electronium model.

Klaus kept his preconception of a moving electron longer than all his classmates but even he, along with all of the other students, was finally convinced that the electron is not moving in the Electronium model. The 'no movement' conception also proved to be stable: both students emphasized in the delayed control interviews that the electron is not moving in the atom and that it is not allowed to move because this would cause emission of electromagnetic radiation. At the end of the teaching, Klaus also commented that:

> 'And in the model of Herrmann [one of the people who developed the Electronium model], it [the electron] does not move, because it is a cloud.'

Thomas stated in a discussion with his peer student in one of the private lessons:

> 'With regard to Herrmann it [the electron] does not move. It is not able to move, it is not possible. Electronium is distributed around the nucleus.'

From these statements it might be concluded that a crucial feature of the Electronium model is that the electron consists of a dispersed substance, and whether this substance is particulate or not is irrelevant for the construction of the ‘no-movement’ conception.

Acceptance of the Electronium conception by students

For Thomas the Electronium model shows a congruent resonance from the early stages of teaching. After the pre-questionnaire, in which the models were introduced briefly, Thomas took the initiative in using the Electronium model in an intuitive way.

Although Klaus preferred a probability model at the beginning, he finally switched to the Electronium model. After the probability and Electronium models were discussed in detail, both Thomas and Klaus, and all their classmates, agreed that they preferred the Electronium model. One repeatedly expressed reason, from both students, for this preference of the Electronium model focused on its substantial, visual appearance. Thus Thomas commented:

> ‘Me too. I also rather prefer the model of Friedrich Herrmann. It is more descriptive. It is easier to imagine. In this model, the electron does not disappear and appear again without one knowing how it managed this [like in the probability model].’

The Electronium model was accepted well by all nine students in the class. Furthermore, both Klaus and Thomas were still able to outline the Electronium model in the control interviews two years after the end of the instruction, which proves the stability of the Electronium conception. Klaus even mentioned that he had given up the old shell conception rather than giving up the new conceptions, which is what is normally observed when teaching the probability model. Klaus made the following comment about the shell model:

> ‘I don’t know, because I have discarded that [spatial shell] model; I do not precisely know it anymore.’

There were two further aspects of the Electronium model that were frequently and spontaneously referred to by both students and thus constituted a strong congruent resonance for the students. These conceptions were well accepted by the students and were stable. The two aspects are:

- *Concerning the charge distribution in the ground state (1s state):*
  The charge density is the highest at the nucleus and decreases with increasing radius.[1]
- *Concerning the change of the charge distribution in the case of a transition between two stationary states:*
  The charge will move away from the nucleus (the charge will be distributed further from the nucleus) if energy is added.

The majority of all students (17 of 26) mentioned spontaneously the decreasing charge density with increasing radius in the post-questionnaire. It is assumed that the high acceptance outcome results from the fact that the new ideas build upon students’ preconceptions. Many explanations were given by students for this characteristic trait of the charge distribution.

The findings for Klaus and Thomas are summarized in figure 1. They explained the charge distribution in terms of attractive or repulsive electrostatic forces. The students also used analogies between atoms and their ideas about the atmosphere or water, where the density decreases with height or increases with depth. The effect of the electrostatic force is seen as being equivalent to the effect of pressure, which is interpreted as compression: the higher the force or pressure, the more the substance is compressed and the higher is its density. The main argument for the characteristic charge distribution given by the two students is that it is simply logical that the charge is distributed like the electrostatic force or field. In using a lines-of-force representation to illustrate the distribution in the atom (see figure 1, right-hand side), the distribution is inversely proportional to r^2 like the acting electrostatic force, but in fact the charge distribution follows an exponential function.

The subsequent introduction of higher states after the introduction of the 1s state was also accepted by the students, although the distribution

[1] Although this description is correct for all states (if the region with nodal areas is disregarded), it is assumed that the students especially imagine the 1s state. One indicator for this is that the students always draw the 1s state when asked for their image of an atom.

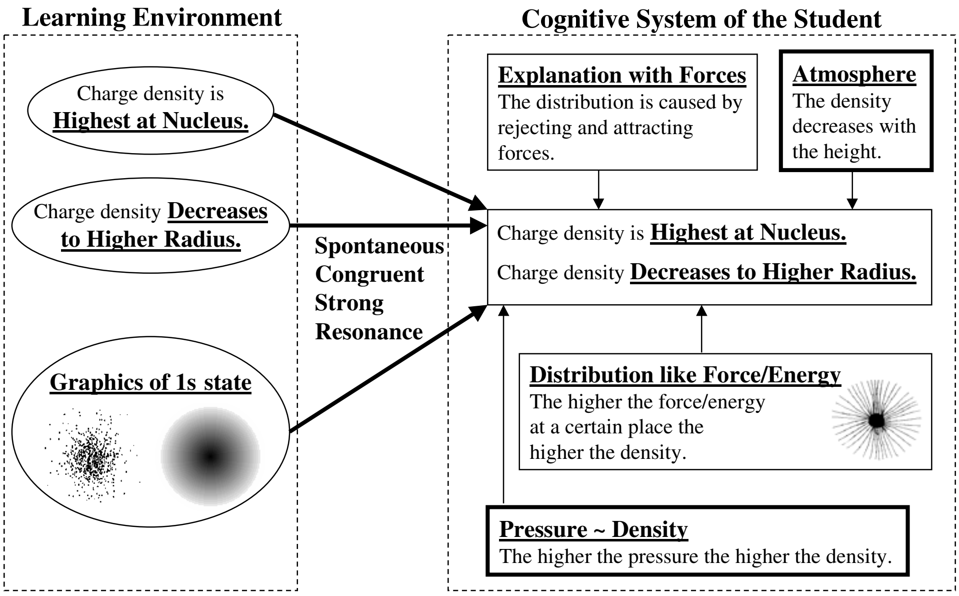

Figure 1. Explanation for the plausibility of the 1s state.

with nodal areas (where the Ψ-function is zero) was not plausible to the students. It was also observed that the students spoke more frequently of abstract states and the energy of those states rather than of the concrete charge distributions. If they referred to the concrete charge distribution they tended to emphasize that the charge was more widespread, or distributed further from the nucleus, in higher states with higher energy. It is therefore concluded that this conception shows strong congruent resonance because it is linked to the preconception that the electron jumps into a higher (in the sense of more distant from the nucleus) orbit, or shell, if energy is added (see figure 2).

It appears that if the teaching focuses on the aspects that are plausible to the students (distribution in the 1s state; the uptake of energy causes a more distant distribution), this supports a high acceptance of the Electronium model.

Final refined teaching hypotheses concerning the Electronium model

The following teaching hypotheses are modified to take account of the above observations.

Teaching hypothesis 1: Liquid–continuous. An analogy between Electronium and liquids may *not* support the development of a conception of Electronium as being continuous rather than particulate in nature.

Teaching hypothesis 2: Movement of the electrons. The Electronium model may support the development of conceptions of atoms in which electrons are not moving if they are in stationary states.

A view of Electronium as being *continuous* in nature may not be necessary for the construction of this conception.

Teaching hypothesis 3: Acceptance of the Electronium conception by students. The distribution of the charge density in the ground state may be plausible to students, which increases the acceptance of the new atomic models.

The visual appearance of the Electronium as a substance may support a high acceptance of an Electronium model.

Recommendations

The teaching of the Electronium model can be characterized as being definitely more successful and effective than the teaching of the probability model. Therefore the Electronium model is recommended as a 'stepping stone' (Brown and Clement 1992) or an 'intermediate notion' (Tiberghien 1997) towards the accepted scientific model.

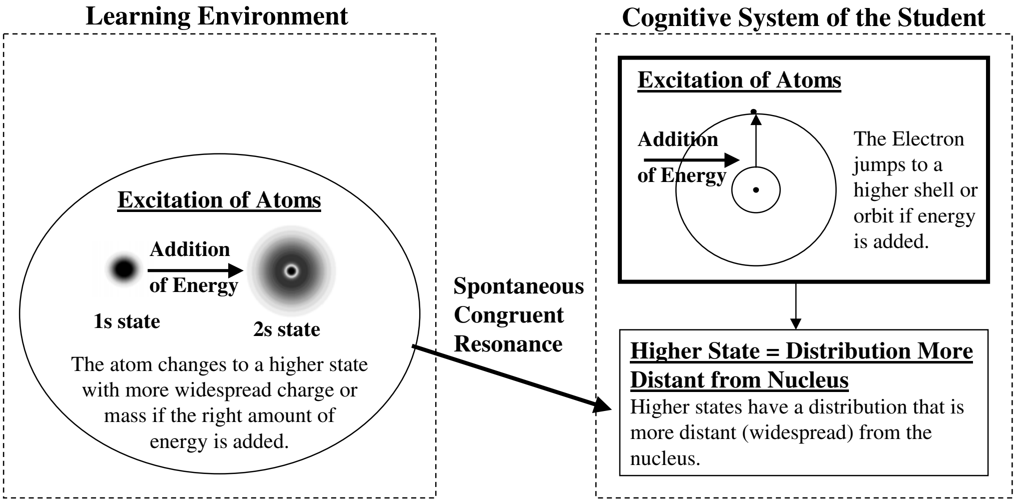

Figure 2. Explanation for the high resonance of the conception 'higher state = distribution more distant from the nucleus'.

Furthermore, a cooperation with chemistry lessons is advised because the questions and preconceptions in the field of atomic physics are highly influenced by previous chemistry lessons. The Electronium model can offer a link to the chemistry lessons and can be connected to a spatial shell model, which is traditionally used in chemistry lessons. A shell is then interpreted energetically and not spatially. All states that belong to one main quantum number n are then interpreted as one shell.

In summary, the Electronium model is seen as offering an interesting possibility to fill the gap created by the lack of quantum atomic models in the UK curriculum. The 'Advancing Physics' syllabus (Dobson *et al* 2000) introduces the strange behaviour of quanta using Feynman's 'many paths' approach instead of referring to wave–particle dualism. This innovative perspective, however, is not transferred to atomic physics. The Berlin approach (Werner 2000) exemplifies how the 'many paths' approach can be extended to bound electrons using the Electronium model.

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