'Electronium': a quantum atomic teaching model

Marion Budde[1], Hans Niedderer[1], Philip Scott[2] and John Leach[2]

[1] Institute of Physics Education, Department of Physics and Electrical Engineering, University of Bremen, Bibliothekstraße, 28334 Bremen, Germany
[2] Centre for Studies in Science and Mathematics Education (CSSME), School of Education, University of Leeds, Leeds LS2 9JT, UK

E-mail: budde@physik.uni-bremen.de

Abstract
For many students, learning quantum atomic models raises difficulties that result from the major differences between quantum-mechanical perspectives and the classical physics view. After being taught the probability atomic model, which is traditionally introduced in Germany in upper secondary school (age 18–19), the understandings of the overwhelming majority of students differ significantly from the intended learning outcomes. An alternative atomic model, the descriptive quantum atomic model 'Electronium', is outlined in this paper, and the way in which it is intended to support students in learning quantum-mechanical concepts is discussed.

Introduction

This is the first of two linked papers that focus on the descriptive atomic model 'Electronium', which was developed, in Germany, to facilitate students' learning of quantum atomic physics. In the UK, atomic models are not explicitly mentioned in the QCA A/AS level subject criteria, nor are they included in most of the A/AS specifications. In the AQA 'B' specification, for example, the amplitude of a de Broglie wave is interpreted as being proportional to the probability of finding an electron at that point. Despite this interpretation, the quantization of energies in the atom is interpreted in terms of fitting a wave onto the orbit of the electron. Furthermore, there is an absence of graphics for quantum atomic models in advanced level physics textbooks (see, for example, Breithaupt 2000). The models that are mainly used are spatial and/or energetic shell models and a Bohr model, which are both very limited. It has been argued (Rebello and Zollman 1999) that the restricted teaching of energy levels without presenting any visual atomic models results in students retaining a classical, mostly planetary orbit, atomic model, and that the explicit teaching of quantum atomic models is therefore necessary to overcome limited classical atomic conceptions.

Learning involves an interaction between the student and what is taught. Furthermore, since learning involves a personal sense-making step, what is learnt is often not the same as what was taught. Although learning is an individual process, there are similarities in the learning of different students. There are certain preconceptions that many students share. It is therefore possible to identify knowledge that is relatively easy or difficult to learn for many students. This study is based on an approach whereby it is assumed that it is possible to analyse previous research

0031-9120/02/030197+07$30.00

on learning in the domain of quantum atomic physics in order to *predict* the students' responses to particular approaches to teaching. The aim is, therefore, to formulate testable *teaching hypotheses* about which teaching approaches may support or inhibit students' learning, taking into account the students' preconceptions.

First of all, an analysis of learning difficulties associated with the 'probability' quantum atomic model is presented, as a starting point to considering the alternative 'Electronium' model. A comparative summary of the key features of the atomic models referred to here is presented in table 1.

The quantum atomic 'probability' model

The probability model is an interpretation of the solutions (Ψ-functions, eigenenergies) of the Schrödinger equation. The absolute square of the Ψ-function multiplied by a volume ΔV is interpreted as the *probability of finding an electron* in this volume ΔV, if the position of the electron is measured. Before a measurement is made, the electron does not have a precise position; the act of measurement produces this position and thereby changes the state of the atom. For this reason it is impossible to make chronological measurements of the position of the same electron, which is in a certain stationary state (e.g. the 1s state). After the first measurement, the electron is no longer in the 1s state and the second measurement of this electron therefore says nothing about that state. According to this model, the electron can no longer be thought of as moving along classical trajectories. The graphical representations (figure 1 shows measurements with the hydrogen atom in the ground state) that are often used to illustrate the model show the position-measurement results for *different* atoms which were in the same stationary state before measurement.

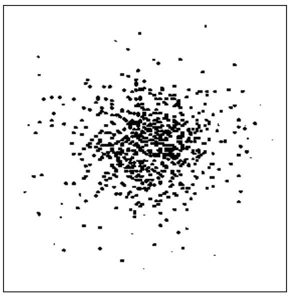


Figure 1. The probability model.

Hence the model makes no statements about the unmeasured or undisturbed atom; it can only describe the results of measurements. In this sense, the question of how an atom appears cannot be answered.

Learning difficulties associated with the quantum atomic 'probability' model

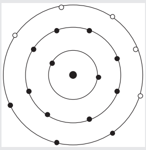
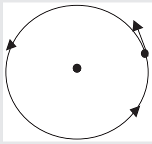
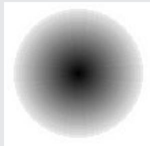
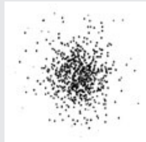
When teaching the probability model two main learning problems emerge:

- Students tend to retain their preconceptions (mainly planetary orbit or shell conceptions: see table 1) or revert to their preconceptions after teaching, and thus there is no long-term learning effect. The planetary orbit preconception seems to be especially resistant to change (Bethge 1992, Fischler and Lichtfeldt 1992, Mueller and Wiesner 1999).
- Students construct alternative conceptions, which differ significantly from the intended models. In particular, they retain the belief that the electrons are moving in the atom. This is even the case for those students who accept that electrons are not located on trajectories in quantum mechanics, as they are in classical physics (Bethge 1992).

In order to account for the origin of these learning difficulties, especially the movement aspect, a mode of analysis has been developed which considers the possible influences of both preconceptions and the taught content on the learning of the student. This analysis is summarized diagrammatically (see figure 2) in such a way that differences between the contents that are taught (on the left-hand side) and the concepts that the student constructs (on the right-hand side) are made explicit. The influence of the taught contents on the student's concepts is described in terms of the concept of 'resonance', which is used to draw attention to the fact that the learning outcome depends on the extent of 'fit' between the taught contents and the preconceptions of the student.

In the following analysis the potential responses of a student to key elements of the teaching are discussed in relation to previously observed learning difficulties.

Table 1. Comparison of the mentioned atomic models: key similarities and differences.

Spatial shell model	Planetary orbit model	Electronium model	Probability model
			
Key characteristics			
electrons are fixed on spherical surfaces around the nucleus	electrons orbit around the nucleus	interpretations of the solutions (Ψ-function, eigenenergies) of the Schrödinger equation	
		electron consists of an extended continuously distributed substance called ‘Electronium’, which is distributed around the nucleus; Electronium is a kind of liquid	makes only statements about the results of measurements; an electron is found as a point object with a specific probability at a certain position
electron is a classical particle		electron is a quantum	
Related models			
	models of Rutherford, Bohr, Bohr and Sommerfeld	electron or charge cloud model, orbital model	
Movement of the electron			
the electron does not move	the electrons rotate on two-dimensional (because of the conservation of the angular momentum) orbits around the nucleus	there is no movement of the electron in the atom in the case of a stationary state	
		in a stationary state the distribution is constant in time	different results emerge from measurement of the position of different electrons; electrons do not move on classical trajectories
Fields of application and limitations			
no explanation of the stability of atoms	explanation of the stability of atoms		
	contradiction to electro-dynamical laws: accelerated electron would emit electromagnetic radiation	contradiction to electrostatic laws: no repulsive forces interact within the Electronium of one electron, but between the Electronium of different electrons	
explanation of excitation and light emission			
no calculation of energy values	calculation of the energy levels of the hydrogen atom, but no predictions of the energy levels of higher atoms	calculation of quantized quantities like energies	
explanation of chemical bonds (Octet rule), but no explanation for bond angles	no explanation of chemical bonds	explanation of chemical bonds	
no explanation for the results of measurement by scanning tunnelling microscopy		interpretation of the results of measurement by scanning tunnelling microscopy as charge or probability density	
not in agreement with quantum mechanics (e.g. Heisenberg uncertainty principle, wave characteristics of electrons)		in agreement with quantum mechanics (e.g. Heisenberg uncertainty principle, wave characteristics of electrons)	

Electron = quantum

In figure 2, the student’s preconception (preconceptions are framed in bold rectangles) ‘electron as a classical particle’ is considered to have a fundamental influence on constructing the concept of movement as part of the probability model. According to the probability model the electron

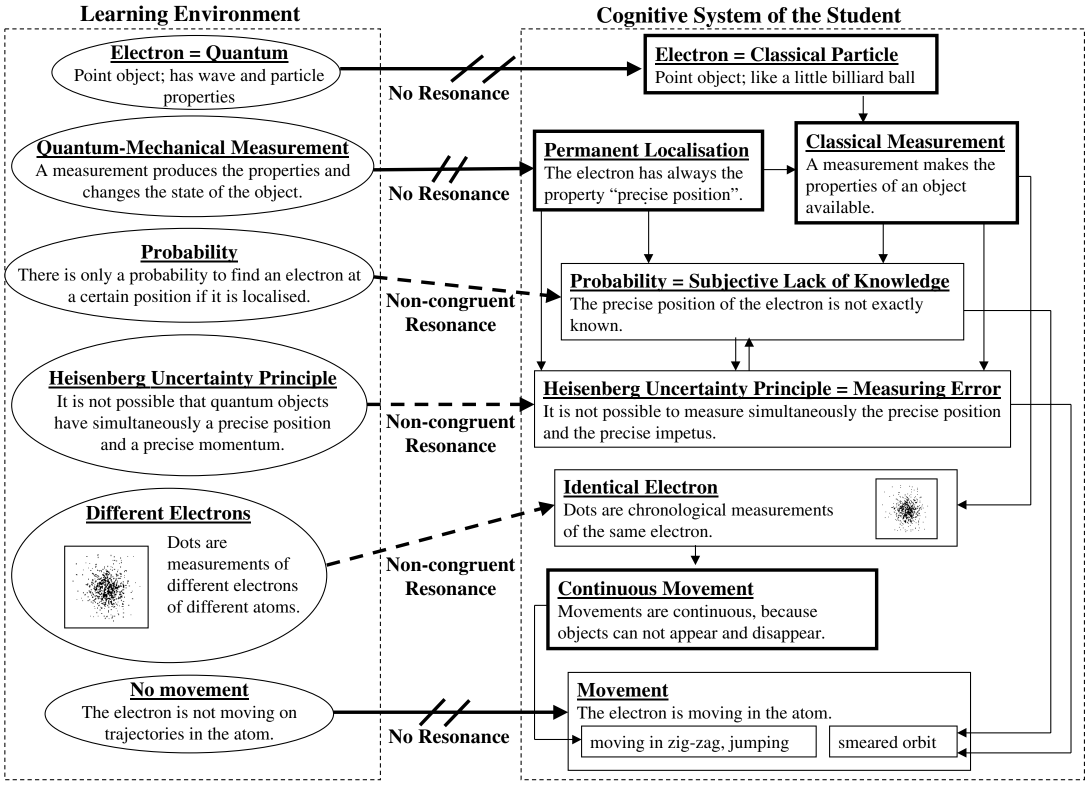


Figure 2. Learning difficulties, which may occur when teaching the probability model, are explained in terms of the student's preconceptions.

is seen as a quantum, which has both wave and particle properties. When teaching this aspect it may show *no resonance* (that means the teaching has no influence on the student's conception), since the student still sees the electron as a little billiard ball. This is traced back to the fact that, for the student, quanta and classical particles are both point objects.

Quantum-mechanical measurement

Because the student sees the electron as a classical particle, which is permanently localized (Mueller and Wiesner 1999), measuring the position of the electron involves making knowledge about the position available. Thus it is likely that teaching about the characteristics of the quantum-mechanical measurement (a measurement changes the state of the electron) will show *no resonance*.

Probability

Teaching that there is only a certain probability of finding the electron in a certain position, if the position of the electron is measured, is likely to show *non-congruent resonance*. This means that the conceptions of the student are influenced by the taught content but differ significantly from it. Thus the student typically believes that the electron does have a precise position, but that there is a subjective lack of knowledge (Bethge 1992, Petri and Niedderer 1998), which results in its position being not known exactly.

Heisenberg uncertainty principle

The student may explain the lack of knowledge about the electron's position in terms of the Heisenberg Uncertainty Principle (Mueller and Wiesner 1999). The Uncertainty Principle introduces the idea that it is impossible for a quantum object to have a precise position and a precise momentum at the same time. Because it is very likely that the student does not share the quantum-mechanical conception of measurement, this is interpreted in terms of measuring errors or lack of accuracy (Mueller and Wiesner 1999) and leads to a *non-congruent resonance.*

Different electrons

If the student retains their preconception of classical measurement and does not understand that a quantum-mechanical measurement changes the state of the electron, the graphical representation (figure 1), which shows the outcomes of measurements of electrons of different atoms, may also cause a *non-congruent resonance*, as the student interprets the dots as a chronology of measurements of the position of the same electron.

No movement

Because objects and classical particles in everyday life cannot just appear and disappear in different places without travelling between them, the student may consider that the electron must jump or move in some form of zig-zag within the atom (Bethge 1992). Another possibility is that the student constructs a smeared orbit conception (Bethge 1992, Petri and Niedderer 1998), in which the trajectory is no longer precise. This conception is influenced by the student's interpretation of the Uncertainty Principle in terms of lack of accuracy (Petri and Niedderer 1998). In summary, teaching that the electron is not moving on trajectories is likely to show *no resonance*.

Having identified these learning difficulties which are likely to arise from teaching the probability model, we now turn our attention to the 'Electronium' model.

An alternative approach to teaching: the Electronium model

The Electronium model is a quantum atomic model, which is also based on the Schrödinger equation. It has been developed for teaching at secondary school level as part of the Karlsruhe Physics Course (Herrmann 2000) and attempts to structure the physics content to take account of students' preconceptions. The preconceptions are not viewed as something to be 'overcome' but are used as a starting point, which can be worked on in order to achieve understanding of the accepted scientific view.

Fundamental to the Electronium approach is a change in perspective, which involves introducing a *substance* model, instead of focusing on a particle model. All the defined extensive quantities (energy, momentum, angular momentum, electric charge, amount of substance, entropy) and the field are seen as a substantial fluid or 'stuff' rather than as an abstract mathematical quantity. Within the atom, the electron is seen as an extended object, consisting of the substance Electronium, which is distributed around the nucleus. Electronium is not particulate in nature but is a continuum with varying density. The absolute square of the Ψ-function is interpreted as being proportional to the density of the Electronium, and in the ground state the density of the Electronium decreases continuously away from the centre of the atom (see figure 3). In stationary states the form of the Electronium is constant with time; there is no element of movement. In the case of a transition from a high to a lower state the charge distribution changes and this redistribution of charge causes an emission of electromagnetic radiation. If the position of the electron is measured, the charge concentrates at a point. $|\Psi(r)|^2$ is then interpreted as a measure of the probability for the transition from the state in which the electron is distributed over the whole space to the state in which the electron is found at that particular position.

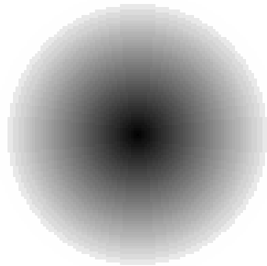


Figure 3. The Electronium model.

This interpretation is not totally new: Schrödinger also interpreted the absolute square of the Ψ-function multiplied by the total charge as the charge density. Chemists also talk about orbitals as 'charge/electron clouds'.

An analysis of the predicted responses of a student to the teaching of key elements of the Electronium model is presented in figure 4.

Extended electron

The fundamental difference from the probability model is that the electron is seen as an extended object instead of a point object. It is predicted that teaching the content 'extended electron is

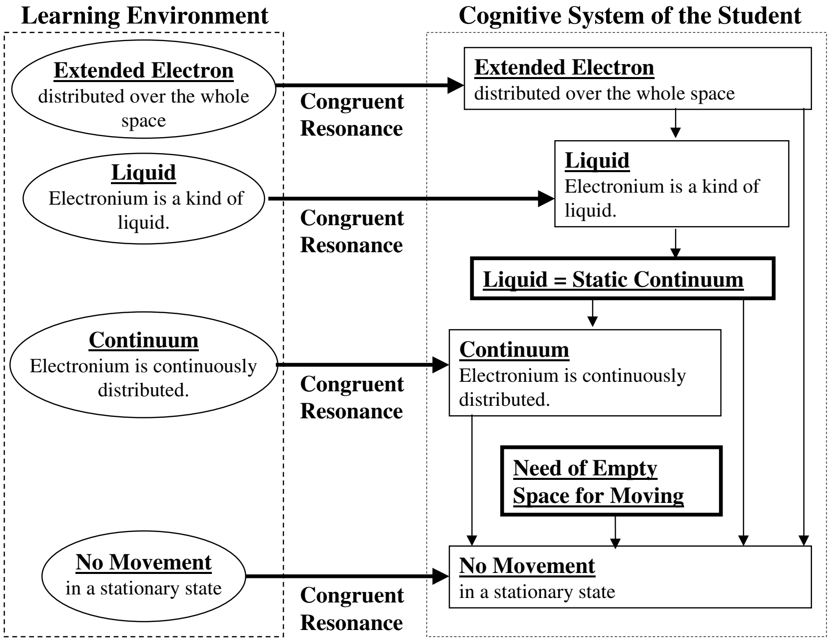


Figure 4. Assumed positive effects when teaching the Electronium model.

distributed over the whole space' will show *congruent resonance* (that means the taught content and the student's conception of that content are equivalent).

Liquid–continuum

Because many students imagine that electron clouds consist of particles, which are the electrons themselves (like a cloud in the sky consists of droplets of water, Harrison and Treagust 1996), Electronium is not introduced as a cloud but as a kind of liquid, with the intention that this will support development of a continuum conception. It is known that students in lower secondary school often conceptualize liquids in terms of a static continuum. Indeed, Fischler and Peuckert (1997) found that 75% of a cohort of students still believe that water is a continuum at the beginning of the upper secondary school level (age 17). It is therefore predicted that if the teaching of the 'Electronium as a kind of liquid' shows congruent resonance, this will support a continuum conception.

No movement

It is assumed that the concept of 'Electronium-as-continuum' will, in turn, support the construction of the conception that there is no movement of the electron in the atom in a stationary state, because of the student's belief that an object needs empty space for movement. Following the findings set out in the previous section, in relation to the probability model, the congruent resonance of the 'no movement' aspect is considered to be one of the main learning goals for this approach.

Resulting teaching hypotheses for the Electronium model

The following teaching hypotheses follow from the analyses set out above. Because learning is seen as a developmental process involving the cognitive system of a student, which is influenced but not determined by the teaching, the hypotheses can only predict the *potential* construction of conceptions.

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.

Experiences with teaching the Electronium model

Because atomic physics is not a compulsory part of the curriculum in lower secondary school in Germany, the Electronium model is rarely taught at the school level for which it was originally developed. The model is, however, used in two different German teaching approaches for the upper secondary school level. One was developed at the Humboldt University in Berlin (Werner 2000), the other at the University of Bremen (Niedderer *et al* 1997).

In the following paper in this issue a case study of the responses of two students to the teaching of the Electronium model, in the framework of the Bremen teaching approach, will be presented. The case will be made that the Electronium model can be considered to offer a successful teaching tool.

Acknowledgments

This article was written during a stay by one of the authors (MB) at the CSSME at the University of Leeds in the frame of the Marie Curie fellowship programme of the European Commission.

Received 1 March 2002
PII: S0031-9120(02)34457-5

References

Bethge T 1992 Schülervorstellungen zu grundlegenden Begriffen der Atomphysik *Quantenphysik in der Schule* ed H Fischler (Kiel: IPN) pp 215–33

Breithaupt J 2000 *New Understanding Physics for Advanced Level* 4th edn (Cheltenham: Stanley Thornes)

Fischler H and Lichtfeldt M 1992 Modern physics and students' conceptions *Int. J. Sci. Educ.* **14** 181–90

Fischler H and Peuckert J 1997 Probleme mit den Teilchen im Physikunterricht *Physik in der Schule* **35** (3) 93–7

Harrison A G and Treagust D F 1996 Secondary students' mental models of atoms and molecules: Implications for teaching chemistry *Sci. Educ.* **80** 509–34

Herrmann F 2000 The Karlsruhe Physics Course *Eur. J. Phys.* **21** 49–58

Mueller R and Wiesner H 1999 Students' conceptions of quantum physics *Research on Teaching and Learning Quantum Mechanics. Papers presented at the annual meeting of the National Association for Research in Science Teaching, March 1999* ed D Zollman pp 20–2 (http://www.phys.ksu.edu/perg/papers/narst/)

Niedderer H, Bethge T, Cassens H and Petri J 1997 Teaching quantum atomic physics in college and research results about a learning pathway *The Changing Role of Physics Departments in Modern Universities, Proc. Int. Conf. on Undergraduate Physics Education (ICUPE)* ed E F Redish and J S Rigden (New York: American Institute of Physics) pp 659–68

Petri J and Niedderer H 1998 A learning pathway in high-school level quantum atomic physics *Int. J. Sci. Educ.* **20** 1075–88

Rebello N S and Zollman D 1999 Conceptual understanding of quantum mechanics after hands-on and visualization instructional materials *Research on Teaching and Learning Quantum Mechanics. Papers presented at the annual meeting of the National Association for Research in Science Teaching, March 1999* ed D Zollman pp 2–6 (http://www.phys.ksu.edu/perg/papers/narst/)

Werner J 2000 Vom Licht zum Atom. Ein Unterrichtskonzept zur Quantenphysik unter Nutzung des Zeigermodells *Studien zum Physiklernen* ed H Niedderer and H Fischler, Band 12 (Berlin: Logos)

John Leach is Professor of Science Education and Director of the Centre for Studies in Science and Mathematics Education (CSSME) at the University of Leeds. **Philip Scott** is Senior Lecturer in Physics Education at the CSSME. **Hans Niedderer** is Professor in Physics Education and **Marion Budde** (pictured) is a PhD student at the Institute of Physics Education at the University of Bremen. Marion Budde studied for eight months as a Marie Curie Scholar at Leeds.