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Learners' mental models of the particle nature of matter: a study of 16 year-old Swedish science students

Abstract

The results presented here derive from a longitudinal study of Swedish upper secondary science students' (16-19 years of age) developing understanding of key chemical concepts. The informants were 18 students from two different schools. The aim of the present study was to investigate the mental models of matter at the particulate level that learners develop. Data was collected using semi-structured interviews based around the students' own drawings of the atom, and of solids, liquids, and gases. The interview transcripts were analysed to identify patterns in the data that offer insight into aspects of student understanding. The findings are discussed in the specific curriculum context in Swedish schools. Results indicate that the teaching model of the atom (derived from Bohr's model) commonly presented by teachers and textbook authors in Sweden gives the students an image of a disproportionately large and immobile nucleus, emphasises a planetary model of the atom and gives rise to a chain of logic leading to immobility in the solid state and molecular breakdown during phase transitions. The findings indicate that changes in teaching approaches are required to better support learners in developing mental models that reflect the intended target knowledge.

Introduction

The work presented here reports from the first stage of a longitudinal study of the developing chemical understanding of Swedish upper secondary (16-19 years of age) science students. The project is undertaken from within the constructivist paradigm (Strike & Posner, 1985), where learning is seen as dependent upon a process where we reflect on previous experiences to create our own knowledge of the world. The learners' own individually created knowledge will here be referred to as *learners' mental models* (Vosniadou, 1994; Gilbert, 1998; Taber, 2003a).

Chemistry as a subject is taught by means of models. Indeed, science can be understood as largely concerned with developing models of aspects of the natural world. Scientific models evolve through the processes of scientific enquiry and discourse, and may be sophisticated and highly abstract. School science as a curriculum subject represents science to learners (Kind & Taber, 2005) and in this process of representation the models of science become transformed (Justi & Gilbert, 2000). *Curriculum models* are the simplified versions of scientific knowledge which are prescribed (for example by examination specifications, or in an official curriculum or recommended textbook) as *target knowledge* for learners at a particular age/education level. Teachers use *teaching models* that may be further simplifications – such as standard diagrams, simple physical models, teaching analogies and so forth (Gilbert, De Jong, Justi, Treagust & Van Driel, 2002).

These teaching models, as well as the curriculum and scientific models, range from those representing phenomena we find in the observable macroscopic world to those representing the theoretical entities (such as molecules) conjectured to exist at sub microscopic levels (Johnstone, 1993) and from very simple to intellectually highly challenging ones. However, it has been shown that the teaching models in Chemistry are not always presented as such by textbook writers and teachers (Duit, 1991; Harrison & Treagust, 2000; Justi & Gilbert, 2000; Justi & Gilbert, 2002). The material is often presented as unproblematic representations of nature, with no explicit acknowledgement that what are being discussed *are* models. Often the scope, limitations or roles of these models are not presented to learners. It has long been recognised (Carr, 1984) that this can be a source of confusion for learners in chemistry. So, for example, not knowing the limitations of these models could be one factor in students commonly developing the alternative conceptual framework reported by Taber (1998a), i.e. the octet framework, were the students over-generalise a limited teaching model (the octet rule) as the basis of an explanatory framework that is applied across fundamental areas of chemistry.

Students then form their own mental model of the aspired target knowledge (i.e. the *student's model*). There has been a great deal of research in science education to explore learners' thinking in scientific topics (Duit, 2007). This programme of research is based in a constructivist perspective that indicates that research into the way learners understand scientific phenomena and make sense of science teaching can inform improved pedagogy (Taber, 2006a). In this work researchers have commonly explored student thinking in depth and reported their findings in terms of representations of the researchers' own models of common features of the learners' ideas (Gilbert & Watts, 1983). In the present study we present our model of the Swedish students' thinking about the particular nature of matter. This model comprises of a conceptual framework constructed from several components, each based on our interpretations of common patterns in the interview data.

Research about learners' adoption of particle ideas

The concept of matter is essential to chemistry, in particular since 'chemistry is a science of matter and its transformations; appropriate understanding of matter determines the students' understanding of principles and theories of physical and chemical change' (Liu & Lesniak, 2004). Several studies on children's developing models of matter, its different forms and transitions have been undertaken over the last decades. This has been addressed in the alternative conceptions literature, and it has been shown to be a fruitful subject for analysing children's learning processes since the macroscopic experience of matter begins in very early childhood.

It has been suggested by Krnel, Watson & Glazar (1998, 2002) that the first step in concept formation regarding matter for young children is the naming of objects and 'primitive action', like 'what can you do to it?' (Mariani & Ogborn, 1990). The next step in concept formation is the separation between properties. This leads to categorization in the form of a concept or a prototype (Krnel et al, 1998) as for example, the prototype/concept 'water' that seems to be a category that, when used by young children, includes all liquids that are clear, can be poured and wet surfaces. Krnel, Watson, and Glazar (1998, 2002) argued that the key to prototype development is distinguishing between intensive and extensive properties in order to separate substances from matter.

Not surprisingly, the main obstacle for learning about matter and its different forms, after formal education has begun, has been shown to be relationship between the theoretical submicroscopic (atomic/subatomic) level and the familiar macroscopic world, or as Liu and Lesniak (2004) described it 'the existing forms' and the 'properties'. One of the conclusions that can be drawn from the findings presented by a range of authors is that the difference between substance, matter and its forms are concepts that are difficult to grasp at all levels and ages, ranging from small children to students at university level (Novick & Nussbaum, 1981).

The research context

The reports of student learning difficulties in understanding scientific models of matter, substance and chemical change have derived from a range of educational contexts, suggesting that these scientific ideas are inherently difficult for students. Whereas matter is a general term that includes any kinds of materials, in chemistry substances are ontological categories of matter that are considered to be unitary and `pure´. Although pure substances are of central theoretical concern in chemistry, most common materials or samples of matter consist of mixtures or composites of different substances. The present paper describes findings from a study being undertaken in the context of Swedish secondary (high school) learning. We believe that it is important to explore developing understanding of key scientific concept areas in different contexts, as such varied contexts offer a 'natural teaching experiment', in the sense of allowing learning to be investigated under different teaching conditions. Cultural effects relating to the differences in curricula (when topics are introduced, and in which order), language and particular idioms, are likely to be influential in alleviating or exacerbating learning difficulties. Studies from different national contexts can therefore provide insights into particularly useful or problematic aspects of pedagogy. The present study should therefore be understood against an appreciation of key aspects of the Swedish syllabus context.

At the beginning of 1990 the Swedish school system was decentralised and responsibilities were transferred from the government to the different municipalities. The municipalities are required by law to provide upper secondary education to all students that have completed compulsory school. Swedish schools are governed by: the school law; a guaranteed number of teaching hours within each subject; national syllabus; national goals and ´instruments to evaluate and control goal fulfilment´ (Dir 2006:19). Municipalities were also given the responsibility to ensure that the provided education meets the national goals. There are two kinds of national goals set out as ´goals to aim for´ and ´goals to attain´. The goals to aim for provide the ´main basis for planning teaching´ (Skolverket Lpo 94) while the ´goals to attain' define the `minimum knowledge to be attained by year five and year nine´ (Skolverket Lpo 94).

The Swedish students in Compulsory school (year 1-9, ages 7-15) are entitled to 800 teaching hours of biology, technology, chemistry and physics combined. The normal practise for schools is to divide these hours equally between subjects. Students are therefore generally given approximately 200 teaching hours of chemistry sometime between the ages of 7 and 15. Of particular relevance to the present study, are the following goals `to aim for´ from the national syllabus for chemistry during year 1-9:

> ‘the school in its teaching should aim to ensure that pupils’:
>
> - ´develop their knowledge of transformation in chemical reactions´
> - ‘develop their knowledge of the structure of atoms and chemical bonding as explanatory models for chemical processes’
> - ‘develop an understanding of the indestructibility of matter, transformation, recycling and dispersion’
>
> (Skolverket Lpo 94).

The objectives are then further developed in ‘goals that pupils should have attained by the end of year five and year nine’: These goals provide the only national guidelines as to at what age the students generally should receive their teaching hours in the different subjects. This is designed to give the schools themselves the opportunity to make decisions as to choice of materials and methods as well as when their natural science teaching should begin, and also the general order of subjects as well as the order of content within the subjects. The form of teaching is highly dependent on the individual teacher - and chemistry can therefore be taught as a single subject or integrated with other subjects such as biology, technology and physics, and these two forms of organisations can sometimes be found in the same school. Among the attainment goals at the end of *year five* are that ‘pupils should’:

- ‘have a knowledge of the concepts of solids, liquids, gases and boiling, evaporation condensation and solidification’
- ‘be familiar with different kinds of mixtures and solutions’
- ‘be familiar with some of the factors that causes substances to be broken down, and be able to give examples of how this can be prevented’ (Skolverket Lpo 94)

The attainment targets concerning chemistry at *year nine* presuppose this basic learning, and include expectations that pupils should:

- have a knowledge of the most important cycles in nature, and be able to describe some dispersion processes of matter by air, water and the ground’

- ´have a knowledge of the properties of water and be able to describe its role as a solvent, and as a means of transport over the earth and by plants,´

- ´have a knowledge of the properties of air and its importance for chemical processes, such as corrosion and combustion, (Skolverket Lpo 94).

The evaluations of goal fulfilment are on an individual basis since the national syllabus states that "at each school and in each class the teacher must interpret the national syllabuses and together with the pupils plan and evaluate teaching on the basis of the pupil's preconditions, experiences, interests and need" (Skolverket Lpo 94).

Grades for both compulsory and upper secondary school are given by a three level scale; pass, pass with distinction and pass with special distinction. No grades are given at the end of year five and for year nine it is the 'goals to attain' that are used for the evaluation of grades. There are no national guidelines for expected progression or level of detail in teaching models or target knowledge within the subjects, except for the above mentioned goals.

For upper secondary school, which is the context for this study, the national curriculum ´goals to aim for` concerning particle theory are stated as follows:

- 'develop an understanding of the relationship between structure and properties and functions of chemical elements, as well as why chemical reactions take place'

- 'further develop their curiosity and powers of observation, as well as the ability in different ways to search for and use their knowledge in applying chemistry in new contexts'

The attainment goals are stated as follows;

- 'be able to describe how models of different types of chemical bonding are based on the atom's electron structure and be able to relate the properties of elements to type of bonding and its strength, as well as to the structure of the element'
- 'have familiarity with and be able to discuss how electromagnetic radiation interacts with matter'
- 'have familiarity with some basic elements, chemical compounds and modern materials, their properties, occurrence and processes, as well as their importance e.g. on the earth's crust or in different areas in society'

The criteria prescribed for the awarding of the different grades are shown in Table 1. Given the descriptive nature of the syllabi goals, the teachers of students included in this study turned to teacher-selected text books for guidance concerning content and to support their teaching.

Criteria for pass	Criteria for pass with distinction	Criteria for pass with special distinction
Pupils use concepts, models and formulae to describe phenomena and chemical processes	Pupils integrate their knowledge in chemistry in order to illuminate the relationship between different areas of activity in society	Pupils integrate their knowledge in chemistry from different sub-areas in order to explain phenomena in the surrounding world
Pupils carry out experiments and investigate tasks in accordance with instructions, and use appropriate laboratory equipment, as well as apply existing safety provisions	Pupils work together over the choice of method and design of laboratory experiments	Pupils apply scientific ways of working, plan and carry out investigations tasks, both theoretically and in the laboratory, interpret results and evaluate conclusions, as well as contribute their own reflections
Pupils present their work and co-operate in interpreting results and formulating conclusions	Pupils process and evaluate results on the basis of theories and hypothesis set up, and carry out simple calculations with accuracy	Pupils analyse and discuss approaches to problem-solving using knowledge from different fields of chemistry

Table 1: Grading criteria for Upper Secondary chemistry in the Swedish system (based on information from Skolverket Lpo 94)

Learning about particle models of matter

In order to illustrate the level of description regarding particles presented to learners in grades 1-9 (ages 7-15) one therefore needs to turn to textbooks in use. Teachers are free to organise the teaching sequence, but textbooks offer a model of progression to guide teachers. Generally there is an introduction that focuses on matter in the immediate surroundings at macroscopic level, such as 'air and water´ in books suggested for years 1-3, i.e. ages 7-9 (Sjöberg & Öberg, 2005). Molecules and states of matter are then introduced in books suggested for year 4-6, i.e. ages 10-12 (Sjöberg & Öberg, 2005). Finally the books aimed at year 7-9 (ages 13-15) address atoms and subatomic particles (protons neutrons and electrons) and ions (Enwall, Johansson & Skiöld, 2004; Sjöberg & Öberg, 2005, Andreasson, Bondesson & Boström, 2005).

The focus of this present study is learning of particle theory by students in Sweden at the upper secondary level. The students who were informants for this study were taught in terms of teaching models of the atom deriving from that proposed by Bohr in 1913 (Petruccioli, 1993). The model is presented as 'the Bohr atomic model' in textbooks for upper secondary school (Henriksson, 2004). For the sake of brevity, we will henceforth refer to this model as 'the Bohr model', notwithstanding our comments about the distortion and simplification of scientific models when they are transformed in teaching contexts (cf. Justi & Gilbert, 2000). This model is first introduced towards the end of the compulsory school (i.e. years 1-9, ages 7-15). The model is then revisited at the start of upper secondary school (i.e. at age 16), with students such as those included in this study. The more abstract and intellectually challenging orbital model is not usually taught until first year university level.

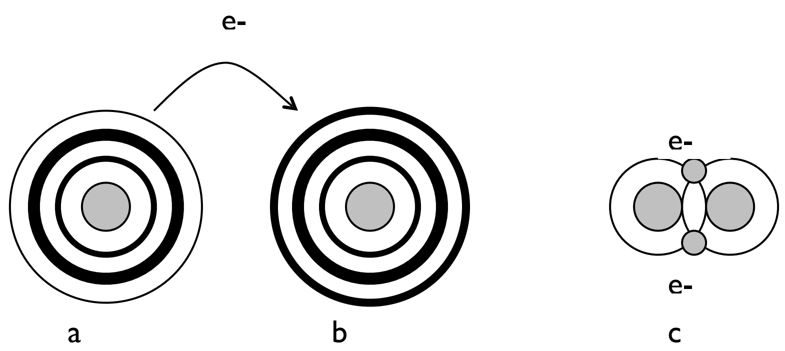
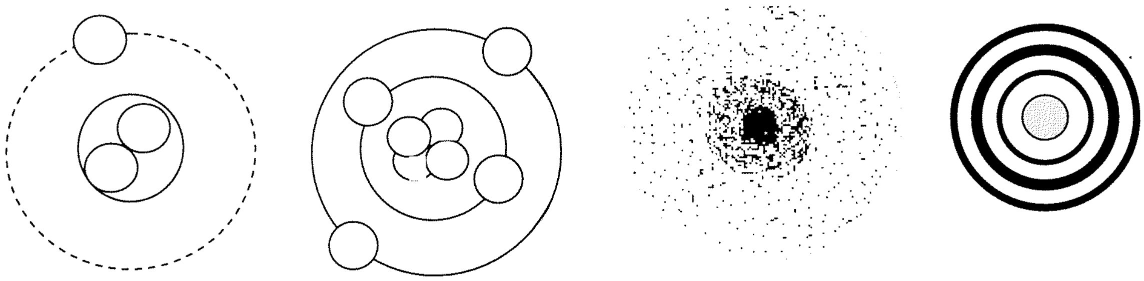


Figure 1: Typical text book images of bonding. Adopted from Henriksson 2004. Figure 1(a) and 1(b) represents a sodium atom and a chlorine atom. The different thickness of the lines in 1(a) and 1(b) symbolises number of discrete charges that can be found in the different shells marked K, L, M, and so on. Figure 1(c) represents the covalent bond between two hydrogen atoms.

The simplified teaching model here referred to as the Bohr model is then developed through the use of the octet rule, in order to explain ionic and covalent bonding, by the use of images such as the one below in Figure 1. It is of interest that the representation of ionic bond formation in Figure 1 takes the form of electronic transfer between individual atoms. This type of figure has been strongly criticised as a teaching model that encourages students to identify ionic bonding with an unlikely hypothetical electron transfer event that bears no relation to common school reactions to form ionic materials (e.g. by neutralisation or precipitation) and does not even reflect binary synthesis, where the reactant elements are not present in atomised form (Taber, 2003b). This approach reinforces common alternative conceptions that make up aspects of the Octet framework (Taber, 1998a) such as assuming chemical reactions involve atoms and occur to allow atoms to fill their shells.



a b c d

Figure 2. Examples of text book representations of some different atoms
(after Henriksson 2004, Andersson, Sonesson, Stålhandske, Tullberg (2003)

The formal teaching models used

Learning about matter in everyday life starts with concrete experience of materials, and progresses by creating prototypes through categorizing matter into more refined categories. However, scientific explanations are usually derived from the more abstract models of atoms, molecules, ions etc. The Bohr model of atomic structure introduced to these students can be found in four different formats (see Figure 2, parts a, b, c and d). Common to representations (a) and (b) is that they show the nucleons; positive protons and neutral neutrons that are round like balls. Additional information concerning mass relationships and electron movement would be found in the surrounding text. The difference between the first two models (a, b) is in the level of detail shown for the nucleus, i.e. whether the nucleus is given its own distinct boundary as a discrete entity. Both the models give the students an impression of an uneven nucleus with a distinct edge that shows no sign of movement and the electron is seen as a particle that moves in 'shells' marked K, L, M and so on. The third option (c) is an atom that shows diffuse and moving electrons and option (d) is a model where the thickness of the lines surrounding the nucleus are related to the number of electrons moving in the different shells. The nucleus in representation (d) is visualised as compact with a distinct edge. The model of a generalised atom presented to the students in books, and by teachers, is based on one or more of the types of representation presented in Figure 2.

Students' mental models of the atom, its parts and their interactions have been discussed in the scientific literature over a number of years (Cros & Fayol, 1988; Pereira & Pestana, 1991; Griffith &

Preston, 1992; Papadimitriou, Solomondiou & Stavvridou, 1997; Taber, 1998b, 2001). Teachers have been advised to take care in *the way they present models* in science classes since students often see models as reproductions of reality (Justi & Gilbert, 2002a). The benefits and potential problems concerning the use of the Bohr model of the atom have been discussed in the literature. The main problems reported among older (13-19 years of age) students' mental models of atomic structure relate to their conceptions of electrostatic interactions (Taber, 1998b, 2001), electronic movement (Cross & Fayol, 1988) and the relative distances between and sizes of subatomic particles (Papadimitriou, Solomondiou & Stavvridou, 1997; Pereira & Pestana, 1991; Griffith & Preston, 1992). Most students seem to have successfully adopted key aspects of this model of the atom – for example, most students recognize that the atomic nucleus consists of positive protons and neutral neutrons (Cross & Fayol, 1988). However, problems have been found in using this model as the basis for developing more sophisticated chemical models. So, for example, a Bohr-type model can lead to confusion when orbital theory is introduced (Taber, 2004). Students seem to create hybrid models where they simply try to adapt the Bohr model to accommodate orbitals. This results in a mechanistic model, where orbitals are seen only as somewhat more complex electron trajectories (Cervellati & Perugini, 1981).

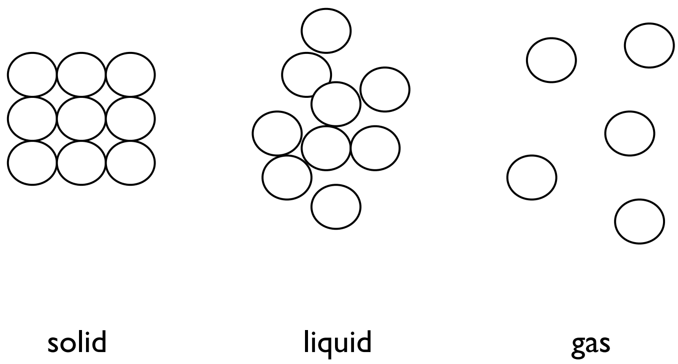


Figure 3. A representation of matter in the three different forms (after Henriksson 2004)

Matter, its different forms and phase transitions

In Swedish schools, the particulate nature of matter and its different forms is then *reintroduced* during the first year of Chemistry in upper secondary school (i.e. at age 16). The teachers of the students included in this study teach by following the general outline and order of content in the textbook of their choice. The model used is again for these students, a general visual image like the one below (see Figure 3).

Supplementing students' macroscopic ways of thinking about matter with a particulate perspective has been shown to be one of the major difficulties in learning about matter, its different forms and changes of state. So, for example, research into student's ideas has shown that for many students matter in all forms is seen as continuous (Novick & Nussbaum, 1981; Andersson, 1990; Renström, Andersson & Marton, 1990).

Where students do adopt particle theory, they may fail to appreciate how scientists use particle models, i.e. to explain the properties of bulk matter in terms of the distinct behaviour of the conjectured particles (Taber, 2001). For example, soft substances may be seen as consisting of soft molecules, or atoms may be considered to burn up and disappear (Andersson, 1990). It has been found that the various properties of different states are often considered to be due to being composed of different materials, or having different molecules (Gabel, Samuel & Hunn, 1987; Papadimitriou, Solomondiou & Stavvridou, 1997), and that students may think that solids have atoms that are packed *significantly* closer together than liquids (Griffith & Preston, 1992). Indeed, a common fault of student representations of fluids (cf. Figure 3) is the relative separation of particles: being over- and underestimated by students in liquids and gases respectively (Pereira & Pestana, 1991).

Previous research has shown that students may hold a range of alternative ideas about phase transition. Such alternative ideas have been found both in terms of macroscopic explanations – i.e. heat changes water into air (Andersson, 1990), water reacts to form hydrogen and oxygen during evaporation and boiling which then, during condensation, can react again and turn back into water – and when particle models are used - e.g. the phase transition itself is due to change in atomic size (Andersson, 1990), or that the number of particles changes during phase transitions (Gabel, Samuel & Hunn, 1987).

Aim of the study

The aim of the present study is to explore the mental models relating to the particulate nature of matter held by 16 year old Swedish students concerning (i) the different states of matter, (ii) phase transitions, and (iii) the connections between (i) and (ii). The study is intended to both elicit the students' mental models on commencing high school chemistry, and to explore the development of these models in relation to the target knowledge in the curriculum. The present paper reports results from the first phase of this project.

Methodology

A qualitative interview study was chosen as the data collecting method since the study investigated the mental models of learners, and the investigation of learners' ideas is considered to require techniques that are able to explore thinking in-depth (Kvale, 1997). Semi-structured interviews are well-established as the basic technique in research of this kind (Gilbert, Watts & Osborne, 1985). The study was undertaken in two upper secondary schools within two different municipalities in the southern parts of Sweden. Participation in interviews was voluntary and the student sample contained both students that have Swedish as their first language as well as non-native Swedish speakers. Only including volunteers was necessary from both a methodological perspective (i.e. to ensure validity of responses during extended interviews), and on ethical grounds, as researchers should consider an interview as 'a gift' both of time, and of a students' willingness to expose potential areas of weakness to a stranger, despite the potential for ridicule and a loss of self-esteem (Limerick, Burgess-Limerick & Grace, 1996; Taber, 2002).

Volunteers and non-volunteers could conceivably tend to differ in characteristics which are relevant to the research. However, in this study almost half of each teaching group (nine of 19, and nine of 22) agreed to take part in the study, offering a reasonable safeguard against interviewees being especially atypical of their peer groups.

All students who volunteered for the study later passed the chemistry course at the end of upper secondary school and the majority received either the grade pass with distinction, or pass with special distinction. When examining the data there were no obvious differences between schools, which suggests that results may be applicable to other Swedish students at this age.

Data collection

The data collected for the results presented here originates from three interview sessions with each of 18 students enrolled into the science program at upper secondary level who were on the verge of beginning their 'Chemistry A' course (inorganic chemistry). All interviewing was undertaken in Swedish by the first author. The first interviews regarding the atom and its particles were undertaken before the students had received any teaching at this level and the interviews lasted for approximately 40 minutes each. Data was transcribed, coded and divided into categories found in the data itself (Strauss & Corbin, 1990). The interviews that concerned particle theory, the different states of matter and phase transitions were carried out according to an approximate schedule shown in Table 2. The selection of points during the course to schedule interviews was based around the organisation of the scheme of work, and so when students would be taught relevant topics. The schedule is only approximate, as it typically took two weeks to complete a set of interviews with 18 students who had limited 'free' time outside of their scheduled lessons.

Interview topic	approximate point in course of interviews
The atom	before teaching at upper secondary level
The different states	5% into 'Chemistry A' course
Chemical reactions	10% into 'Chemistry A' course
Phase changes	25% into 'Chemistry A course'
Electrochemistry	75% into 'Chemistry A course'

Table 2: The approximate schedule for interviews used in the longitudinal study. This paper reports on findings from the first three interview stages.

In the first interview session the students were asked to draw their image of a generalised atom, and this acted as the focus for a subsequent discussion. For the subsequent questions the students' own words were used to phrase follow-up question during interviews, to verify word meanings and establish student models of subatomic particles, electrostatic interactions and movement. A variety in intra-interview techniques were used to verify the interviewer's interpretations of student responses to the main questions. These included reflecting and rephrasing responses, and follow-up questions that would be considered 'leading' if used as opening questions (Kvale, 1997). An example of a leading follow-up question would be 'Do subatomic particles affect each other?'

The two following interviews concerned substances in solid, liquid and gaseous state, where the students were asked to draw an image of a general solid and the following main questions were: 'Why is a solid, solid? a liquid, liquid? and a gas, a gas?', 'What is the difference between the three phases?', 'What are the differences between phases in this room at constant temperature?'

Analysis

Interviews were conducted, transcribed and analysed in Swedish. All results reported here use English translations of the data and analysis prepared by the first author. The interview transcripts were analysed by the process of open coding (Strauss & Corbin, 1990). Common themes were identified in students' responses, and these are reported and discussed below. These themes have been used to construct a model that represents common features in student thinking among the sample. This model takes the form of a conceptual framework that represents (a) the commonly held mental model of atomic structure, and (b) related specific conceptions about particle movement and interactions.

Results

Conception elicited in interview	number of students / 18
The nucleus does not move	15
The nucleus takes-up a significant proportion of the volume within an atom	18
Electrons only move between shells not within shells	9
Electrons move between shells (as a matter of course) as well as around the nucleus	9
The particles represented by circles in figures showing particle arrangements in student textbooks are atoms	12
No differentiation between behaviour of atoms and molecules in phase change	6
Diagrams representing particles in a solid as tightly packed are understood to imply that there is no scope for any particle movement (such as vibration).	17
Particles do not move in the solid state	13
Student drawings of particle arrangements reproduce under/over estimation of particle separations found in student textbooks	18
Liquids are atomic	10
Gases are atomic	10
Differences in phases at constant temperature is only dependent on particle density	13
Increased particle motion can only derive from energy transferred through heating by the sun or a Bunsen burner	18

Table 3: Frequency of notable conceptions elicited in the study

In this section we present the results of the study. In particular we highlight those conceptions that we elicited during the interviews that we feel are of interest because they are clearly inconsistent with the target knowledge presented in the curriculum (i.e. alternative conceptions) or because they seem to indicate apparent confusions or misunderstandings that are likely to impede effective learning of curricular models (cf. Taber, 2004). The incidence of these significant conceptions among the 18 interviewees is summarised in Table 3. The raw numbers in Table 3 should be considered alongside the more nuanced discussion of our findings below.

In the subsequent section we will consider how many of the distinct findings from the study reported in this section can be understood as part of an overall model of how these Swedish high schools students understood particle theory.

Student mental models of the atom

The variations in student drawings are represented by the exemplars shown in Figure 4.

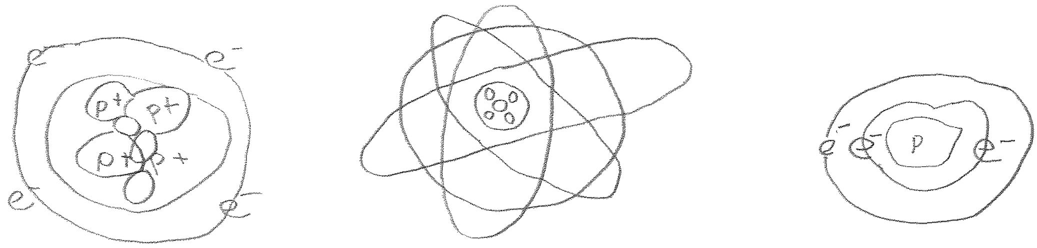


Figure 4. Examples of all the variations of the students´ own drawings of the atom.

The students included in the study used the labels neutrons, protons and electrons to describe the subatomic particles included in their drawings. Many showed understanding of the three dimensional structure of the atom by demonstrating a sphere with the use of their hands. The atomic nuclei was seen as composed of neutrons and protons that were either circular, or had no shape at all but were contained inside a round ball-like shape. The same kind of figures can be seen in publications from Justi and Gilbert 2000, and in the textbooks commonly used in Sweden (see Figure 1). All of the expressed atomic models included a distinct nucleus, that for 15 (of the 18) students lacked internal movement.

> 'The nucleus does not move… it is the electrons that are moving. The atom itself is also still… it is just the electrons that are moving'

> 'electrons move around the nucleus it is almost like the sun and the planets'

The nucleus was seen as having motion by two of the 18 students and one of the students saw the nucleus as a form of container. He had moving protons and neutrons, but the nucleus itself was immobile. When asked to explain he said:

> 'it is like a rubber ball with rocks in it'

All 18 students' diagrams showed an over-sized nucleus in relation to the overall size of the atom. Scientific models often represent details out-of-scale for clarity (they are models, not scale replicas), and the schematic representations in books often show the same distortion, so drawing the atom this way need not imply students believe such models are to scale. However, in view of the research showing students commonly lack a sophisticated appreciation of scientific models (e.g. Driver, Leach, Millar & Scott, 1996), this is a feature worthy of note. Only one of the students mentioned that the scale in his diagram was out of proportion.

> 'in reality if the nucleus was here then the electrons would be on the other side of the wall' (2 metres away)

Some of the students reported electrostatic interactions within the atom suggesting some understanding of the forces between charges:

> 'the electrons are pulled towards the nucleus'
>
> 'the protons repel each other'
>
> 'there is a form of force or attraction between the electrons and the nucleus'

Although in one case this type of interaction was misidentified as 'the same force that attracts the planets towards the sun'.

For most of the students, however, the focus of student thinking about the subatomic particles appeared to be on positive and negative charges in an atom *cancelling* each other out and thereby *creating a balance*:

> 'they are supposed to cancel each other out somehow'
>
> 'there are equal amounts of protons and electrons to keep it in balance'
>
> 'there is always the same number of protons as electrons so there is a balance'
>
> 'If there were more positives than negatives then something would happen to the atom … it could not be an atom any more'

The neutrality of the atom is a significant teaching point, but seems to have been adopted by these particular students more as a central principle (cf. Taber, 2003b), rather than a consequence of the atom comprising oppositely charged particles that exert forces on each other.

The neutrons were seen by all of the students as having some role in maintaining the stability of the structure, although how this was achieved seemed to be mysterious ('the neutron is stabilising the nucleus… but I don't know how'), or at best vaguely appreciated:

> 'the neutron is neutralising'
>
> 'the neutron is balancing the atom somehow'
>
> 'the neutron is a little thing that has to be there so the nucleus gets fixed'
>
> 'the neutrons are just small things that make it [the nucleus] stronger'

To summarize our interpretation of students' answers gives rise to a description of the common form of mental model inferred from these learners' responses: *Atoms have a round three dimensional structure with large immobile nuclei surrounded by moving electrons. Inside the nucleus one finds protons and neutrons. There are equal numbers of protons and electrons to keep the atom in balance. The neutrons stabilize the nucleus.*

All students' mental models involved electrons moving outside the nucleus. Nine (of the 18) students saw the electrons as only moving around *within* shells, while the other nine held a model where the electrons *also* moved *between* shells when energy was added.

The different states

As well as asking students specifically about their ideas about atom, the interviews also explored their thinking of how particle models are used in chemistry to explain the existence of states of matter and changes of state. We found that none of the students showed a sound understanding of matter in the three different states. Examples of students' representations of the states of matter at the submicroscopic level are reproduced as Figures 5a and b.

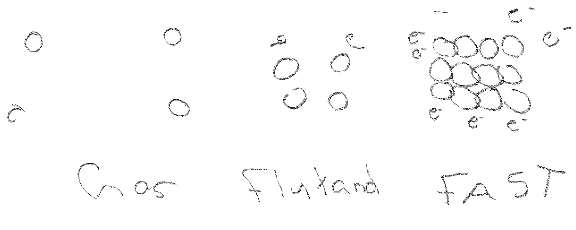


Figure 5a

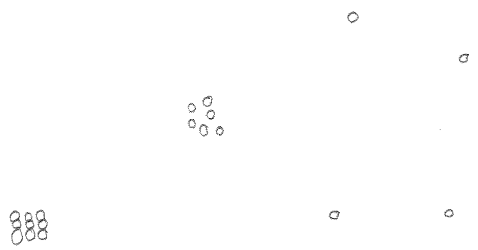


Figure 5b

Figure 5a and b. Examples of a student's representation of matter in different states: gas, liquid and solid.

Distance between particles

The difference in distance between the circles represented in students' drawings for *the solid state* had a reasonably good correspondence to the textbook model for nearly all (17/18) of the students, as can be seen in the examples in Figure 5 compared with Figure 3. The round balls in the solid state were seen as being close enough for the electron shells to overlap or touch one another. The exception was one student who explained that,

> 'the solid is mostly empty space with atoms flying around… I wonder what holds it together really…'

This is an interesting comment, bearing in mind Carr's (1984) notion of model confusion. Taber (2006b: 370) has described the

> "frustration that some learners feel when they are asked to explain the nature of solids in terms of the close packing of particles, and yet to explain thermal expansion in solids in terms of how those same particles are able to freely vibrate (which is often accompanied by diagrams that imply considerable free space between the particles)"

The visual image and textbook description of the close-packed solid state seems like a model that is easily adopted by the students. One of the reasons for this maybe that the model has good correspondence with the students' experienced macro-level understanding:

> ´you can touch it'

> ´I can't feel it moving and there is no noticeable space´

The liquid state was represented with the circles (showing particles) being arranged with a larger distance between particles than the solid state. The distance between the circles representing the gaseous state ranged from the images reproduced (Figure 5) to a distance that was seen as too large to fit on to the (A4) drawing paper. This corresponds well to the findings of Pereira and Pestana (1991) when they reported the over- and underestimations of the distance of particles in liquid and gaseous state respectively. *To summarise: the distances between particles represented in student's models had good correspondence with the textbook representations of particles in the different states of matter.*

Movement in solid, liquid and gaseous state

13 (of 18) students believed that there was no movement of atoms in the solid state. Three of the students assumed that there was some form of atomic movement in solid state and two did not know. Among those students who reported thinking that the atoms could not move, some simply explained this in terms of the atoms being 'packed together' or 'close together' or 'stuck',

> 'the atoms are stuck… they are bigger and stronger that way'

For these students it seemed to be the sheer proximity of other atoms that prevented movement. Only one of the students invoked a specified physical force to explain why the atoms were stuck

> 'they are stuck together with some form of magnetism'

Another of the students recognised some form of, unspecified, 'attraction',

> 'the atoms in the solid are not attached to each other they are in some form of half irregular pattern and there is a form of attraction between them…the nucleus is stuck and the electrons are floating in between them…like atoms in a glass they have nowhere to go they are stuck'

At least two of the respondents who thought that the atoms 'do not move [because] they are stuck in the solid', seemed to hold mental models where the atoms were embedded in some other material,

> 'well… there is like matter around the atoms that keeps them in place'

> 'they are attached in some substance of some kind'

This again seems to reflect a common alternative conception that is typically found among younger students (Renström, Andersson & Marton, 1990), where learners appear to form an intermediate model of matter that includes particles, but retains some continuous matter as a substrate into which the particles are located (see Figure 6).

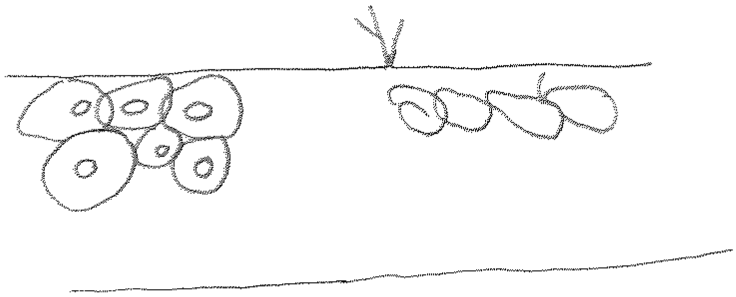


Figure 6. The frame of matter that restricts atoms in the solid state 'well… there is like matter around the atoms that keeps them in place'.

Some of the students, whilst claiming that atoms did not move, did point out that *within* the atom there would be electron movement, i.e. that 'the atoms are immobile but the electrons are moving around in the shell',

> 'they might move a little [pointing at the outer shell of electrons]…but they are very close together'

In one case, an explicit analogy was made with the solar system,

> 'the atoms do not move… it is the electrons that move around the nucleus it is almost like the sun and the planets… the nucleus does not move either'

As discussed below, the sun can only be considered stationary if a particular frame of reference is adopted. One of the students was very emphatic in explaining that the atoms did not move relative to one another,

> 'I think like this…the nucleus is immobile…while the electrons are moving around… the nucleus is in the same spot the whole time… the whole structure also moves… but [pointing at two nuclei] they do not move relative one another'

Even the three students who felt the atoms in a solid moved, appeared to have difficulty in imagining how this was possible. So one student appeared to feel that the familiar macroscopic properties of solids did not leave scope for much movement.

> 'I think it moves but not much… the solid is solid… you can touch it'

Another implied that atomic movement was inconsistent with the hardness of solids,

> 'it is a lot of atoms … that move … if it is a softer substance … they are further apart so they can move more'

The other student who admitted atomic movement was able to form a congruous mental model of how the atoms could move in a solid by suggesting a move of movement that did not require any change of position!

> 'the atoms in the solid moves… like this' [the student shows a slow spinning motion with his hand]

A key finding then is that students' reports suggest that most hold mental models of the particles in a solid that show little movement except for electronic movement.

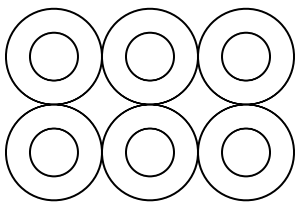


Figure 7. Representation of the students' drawings of a substance in solid state. The image shows large nuclei surrounded by mobile electrons.

What do the circles represent to the students?

The circles shown in representations of solids were found to be confusing for the students. Most of the students saw the round balls in the solid state as discrete atoms (rather than ions or molecules). One of the reasons for this might be because atoms are usually represented as circular (whereas when molecules are explicitly represented they are often shown with a more complex shape). Nonetheless, although the students' general explanations of matter originated from an atomic view, 13 (of the 18) students' answers referred to some form of molecules, or to bonding or attraction between the atoms in the solid state. The remaining five students saw solids as atomic without any form of bonding or attraction between atoms, or gave no explanation at all.

During the discussion of the different states it was found that 10 of the 18 students considered liquids as atomic. The students used water as their example of a liquid. The bonding, attraction or force (that 13 of the students had recognised in the solid state) was now perceived to be gone, and the atoms were seen as moving freely but still being found relatively close one another,

> `the atoms are not structured in the liquid… in the solid they are…in the liquid the atoms are quite far apart´

> `they can't be attracted to each other [student points at one atom] when they are further apart´

> `it is like having 20 kids in a gymnasium if they stand still they can feel each other but then they start moving more and sort of run around and push away from each other and then they don't feel each other anymore´

Previous research has suggested that students often adopt an ontology of the submicroscopic world that gives priority to atoms (Taber, 2003b), for example commonly making an 'assumption of initial atomicity' when conceptualising reactants in chemical change (Taber, 1998a), and we found that these Swedish students would consider liquids as atomic,

> `in a liquid each atom wants more room so there is more air between the atoms´

This example again reflects the notion that atoms are embedded in matter, i.e. a hybrid model of matter at the submicroscopic level where atoms supplement rather than constitute the basis of what appears continuous matter at the macroscopic level (cf. Renström, Andersson & Marton, 1990).

Six of the students did not appreciate the difference between atoms and molecules and two saw liquids as a 'small groups of atoms'. An understanding of the nature of pure substances at the submicroscopic level requires an appreciation of the relationship between atoms and molecules (and ions where relevant). Where students lacked this understanding, they were not able to appreciate how a material comprised of different types of atoms could be a single substance (cf. Briggs & Holding, 1986),

> `a liquid is two substances oxygen and hydrogen´

> `a liquid … it has the nucleus [the student is drawing the nucleus of one atom and adds the electron shell] and then it is together with the other one [the students then draws one more nucleus and its electron shell]… there are two substances together´

The gaseous state (Figure 5) was seen by 10 students as an atomic state. Here the students turned to air as their context for discussing gaseous substances.

> `gases are atomic´

> `well it looks like this, a lot of atoms' [drawing discrete separated atoms]

> `the atoms are flying around everywhere in the gas´

Some of the students' responses suggested that they were still at a stage of making sense of particle models. So one student apparently felt the need to argue that a gas would contain lots of particles,

> `it can't only be one…because there is oxygen everywhere… it can not be only one really big atom … there has to be a lot of little ones that are every were… one by one´

Others seemed to find that imagining a particle model of the gaseous state cued thoughts about atoms that would interact in reactions,

> `a gas looks like this lots of atoms together…next to each other… and the electrons shift between them…and a new substance forms … atoms disappear and more atoms show up because they all want to have full outer shells´

> `take the air… it is oxygen… the atoms are free there… very free… and there is a lot of reactions going on up there…and I probably eat quite a few too…Do I eat them?´

This latter response seems to combine the assumption that gases are atomic, with awareness that 'free' atoms are seldom stable.

One of the students who did seem able to conceptualise a gas as molecular, appeared to draw upon a more familiar system as an analogy,

> `if I had one more oxygen atom then… I guess they would have an effect on each other but … they would be on the same distance from each other the whole time like the moon and the earth except closer´

To summarise: the diagrams showing arrangements of circles that had been presented to the students (see Figure 3) were reproduced by the students (through their drawings) with the circles being considered by more than half of the students as discrete atoms held together by some form of bonding or attraction in the solid state. In the liquid and gaseous state more than half of the students considered that there was no the bonding or attraction between the atoms.

The effect of heating

The mental models of particles in the different states found in this study then show that the students have, again, adopted what they perceive as characteristics of the taught model shown in their textbooks and by their teachers. The textbook models presented for these students – configurations of circles - gave these students the impression of a structural breakdown from a system of many atoms/particles in the solid state to effectively free atoms in liquid and gaseous state,

> \`there is a picture in the book… in liquids and solids the atoms have shorter distances between each other than in the gas ´

> \`the atoms are closer it is a solid and the in the gas they are dispersed and fly around´

The differences between solid, liquid and gaseous state were mainly (13/18 students) seen as due to different levels of energy resulting from increases in temperature.

> \`it has to do with heat and how much energy they get out of the heat they will move more and they change phase´

> \`heat, heat is added and they change phase´

> \`the sun, they change phase when they are warmed by the sun´

The 'added heat' in this case gave rise to an increase in particle motion (which, as discussed above, was generally considered inconsistent with the solid state) and therefore, students concluded, a larger distance between particles, and so a decrease in the density of the substance,

> \`In the gas they have expanded from each other … they move faster´

> \`Density decreases… the atoms become more scarce…well they are probably far from each other … they move more´

Three of the students could offer no explanation as to what the difference between states could depend on. One of the students regarded it as just a coincidence and one suggested that gases are made of atoms with fewer protons and so the gas is therefore lighter,

> `Atoms are different [from each other]… and are meant for different things´

> `There is more gas in those who have less number of protons … of course that is the way it is Hydrogen is gas… Helium is gas… and they have few (protons) … oxygen don't have many either … there they are lighter… they do not weigh as much…´

When asked to explain the differences between solid, liquids and gases at constant temperature the students mainly (13/18) used density, as in less spacing between particles, as the reason,

> `there are very few atoms in the gas´

> `In a solid the molecules are much closer packed than in gases´

> `they [the atoms] are not so close and they move in a gas´

A change in state then, for these students, was primarily seen as a change in density

> `a substance disappears and it becomes lighter´

> `they have more energy [in gaseous form] and they [atoms] move … in the solid there is more on the same surface… a higher density´

To summarise: Another key finding from our study then was that in student thinking the differences between states on heating are due to a breakdown of a system of closely related circles (atoms) to a system where the distance between the discrete circles increase.

What happens when energy is added?

It was found that all 18 students saw the only way energy could be transferred to materials was as 'heat energy' deriving from an external source such as the sun, a Bunsen burner or a hot plate.

The result of the energy input on the particles was, for these students, an increase in movement. All 18 students suggested that added energy leads to increases in motion. However, the specific kind of motion that the students suggested varied considerably. A couple of the students believed that atoms themselves expanded on heating, `but these atoms can become bigger or smaller…´

`it moves [the atom] and becomes bigger´

This is a conception previously reported (Briggs & Holding, 1986; Griffiths & Preston, 1992). Official guidance to UK teachers working with 12-13 year-olds refers to "a very common misconception is that particles themselves expand on heating" (QCA, 2000: 5). As was discussed above, the Swedish curriculum is not highly prescriptive in terms of when topics should be met, and this may explain why more advanced students demonstrate alternative conceptions addressed at a younger age in more structured curriculum contexts.

Three of the respondents associated heat with some type of increased motion ('it moves, heat means motion'), but offered only non-specific associations,

'it moves more… that is just the way it is'

'something moves quicker than the other'

Another of the students specified that it was atoms that moved, but sought some additional material mediation to make this possible,

'there must be something… that comes in between the atoms and makes them move'

For a number (seven) of the students, the direct effect of heating was to change the motion *of the electrons* rather than the atoms

'all electrons are moved around'

'the electrons move depending on heat …or … temperature … if *you heat it up* they move faster and when it gets colder they slow down'

One of the students added a caveat that although the electron movement increased, that needed to be *within* their existing confines:

'I don't know if the atoms move but the electrons move … in the liquid state they should move the same… because if they moved in-between shells then… they would change substance and then there would be more of one substance than the other'

Other students attempted to make sense of their teaching somewhat differently, so for two of the respondents, electrons were actually emitted from the atoms or molecules present:

> 'the more energy you add to the atom the faster the electron moves… and if it gets extra energy then this electron [pointing at an electron in the outer shell] jumps out and light is emitted when the electron moves back in… the heat energy becomes light'

> 'if it is ice then you have not added any energy…and then the electrons move slowly but when you add energy then it is transferred to motion and heat so the more energy you add the more movement you get and then this flies off'

Two other respondents actually went on to describe chemical change:

> 'the electrons spin more when heat is added and the molecule separates'

> 'the electrons are moved around…the nucleus wants electrons so the electron finds new ones and leaves and the there is a reaction'

To summarise: according to the students' ways of thinking, energy added to the system mainly increases electronic movement.

Modelling Swedish 16 year-old students' thinking about the particle nature of matter

Interviews can provide 'snap-shots' into student thinking, and it is always important to appreciate that researchers attempting to make sense of comments elicited from students are involved in a process of active interpretation of data. Assuming that students understand our questions, and are motivated to offer accurate and full responses, and that we are able to record and transcribe responses accurately, then the analyst is in a position to attempt to interpret these comments to build models of the learners' thinking. Despite the inherent opportunities for this interpretive process to break down, semi-structured interviewing is an interactive process that offers both researcher and research considerable scope for checking on the meanings of the other, i.e. 'constant transactional calibration' (Bruner, 1987: 87).

However, even granting the strength of interviewing as a research technique, students are only able to tell us what is in their mind at that point in time. Learners may have confused and nuanced understandings, some of which may be difficult to verbalise, and may even hold manifold conceptions of the 'same' idea (Taber, 2000a). Even when interpretation of our data is trustworthy, it can offer only partial insights into student thinking.

These caveats do not undermine the value of looking to offer models that represent our findings, but rather suggests it should be borne in mind that such representations are (a) like all such models – partial, schematic versions of a more complex phenomena; (b) like all scientific knowledge claims – provisional, being based on the currently available evidence, and open to be being refined and modified by further research. This is not presented as an apology: best available knowledge is better placed to inform curriculum development and teaching than ignorance, and any research-based model can act as a starting point for further research. In this spirit we offer a conceptual framework reflecting common themes in Swedish students' thinking about particle models used in chemistry, based on the sample interviewed in our study (see Table 4).

The connections between features of student thinking

The students' responses in the interview give rise to four common conceptions that have the potential to affect another. The first conception is a model of circular atoms with large immobile nuclei and moving electrons. The electronic motion is either purely circular or also allows movement in between shells. The second conception is that there is no, or very little, internal energy related to the particles, except for the electronic movement. The third conception models the difference between solids, liquids and gases as a breakdown in structure due to added energy that gives an increase in movement.

> `they separate from each other so it becomes like hydrogen and oxygen and that is lighter than water so they become gases´
>
> `water is a good example hydrogen and two oxygen that separates when they become gases and then they reassemble to liquid form again´
>
> `liquid water, that's atomic´

The fourth conception sees added energy manifested as an increase in electronic movement. When these conceptions are combined in learners' mental models they can give rise to a chain of logic that for the students' leads to 'added heat' necessarily resulting in molecular breakdown due to an increase in electronic movement: 'when you add energy the electrons move more and… the molecule falls apart'.

Focus	Conception	Comment
Basic unit:	*matter comprises of particles - the basic unit being atoms*	an atomic ontology, atoms given primacy as particles of interest
Atomic structure	*atoms are three dimensional spheres*	reasonable first order model
	they comprise a large nucleus…	not clear if students appreciate distortion of scale
	…which is comprised of protons and neutrons…	matches appropriate target knowledge
	…and surrounded by electrons	matches appropriate target knowledge - but a limited model if used in isolation
	the number of electrons equals the number of protons	matches appropriate target knowledge
Dynamic aspects of the atom	*the nucleus is immobile*	not clear if this reflects an absolute judgement
	the electrons are in motion around the nucleus	matches appropriate target knowledge - but a limited model if used in isolation
	energy given to atoms increases electronic motion	only recognises one type of atomic energy; seems to be an inappropriate distinction between 'energy' given to atoms, and heating states of matter (see below)
Internal interactions	*the electrons and protons balance*	matches appropriate target knowledge (if focus here is on electrical charge)
	neutrons stabilize the nucleus in some way	matches appropriate target knowledge – although tends to be vague
States of matter	*represented by circles*	acceptable as a first approximation, but not clear how these circles are meant to relate to the atoms seen as fundamental particle units
	are characterised by particle arrangement / density	matches appropriate target knowledge - but limited in ignoring bonding between particles
	little movement of particles in the solid state	ignores vibrational modes and link to temperature in solid state
	adding heat increases distance between atoms	over-simplistic, as does not provide mechanism, or offer basis for distinction between melting and boiling

Table 4: A conceptual framework reflecting common themes in Swedish students' thinking about particle models used in chemistry

Within a constructivist perspective on learning (e.g. Taber, 2006a), new information is generally interpreted to make sense within existing conceptual frameworks. Students' construal of the atom as having electrons moving around a fixed, immobile nucleus may well influence how students interpret teaching about the effects of heating on materials. For some of the students there seems to be an attempt to seek coherence between the notions that heating increases motion, that atoms are immobile (so the motion must be electronic) and knowledge that when electrons move between species, chemical change (rather than just warming) occurs.

Although heating can initiate chemical change, this is a more complex and less common phenomena than heating leading to a change of temperature or state. One interpretation of these responses is in terms of the mental simulations that students are able to form to visualise the sub-microscopic world, drawing on the repertoire of conceptual tools available (Gilbert, 2005). This may partly derive from generalised textbook models (with unspecified 'particles' in the solid state) and the exclusion of intermolecular bonding in discussions regarding the different states for younger learners (ages 7 to 15).

Where students' conceptual repertoires do not include a mechanism for explaining warming (as they see atoms as immobile) or change of state (where they lack a clear conception of appreciate intermolecular forces), but do encompass mechanisms for chemical reactions (based on electron transfer etc.), then the mental models they are able apply when trying to visualise chemistry at the submicroscopic level are constrained.

In other words, if the 'conditions' of such a visualisation include (i) atoms being immobile, (ii) heating causing movement, (iii) electrons moving, and (iv) electron transfer as occurring during reactions, then 'running' the simulation (imagining what happens at the atomic level when the substance is heated) could well lead to this outcome. A different outcome may be reached by those with conceptual repertoires that allow them to conceive of ways electron movement could be increased within the atom (e.g. where an option of electrons moving between shells was available), or through electrons leaving temporarily, but then returning - emitting the energy acquired through heating.

It should be reiterated that the framework represents the researchers' interpretations of common themes in the data, and it is not suggested that all of the informants would match all aspects of the framework (Taber, 1998a). Although this model of student thinking might be labelled an alternative conceptual framework, it is interesting that many of the conceptions making up the model were not in themselves 'wrong' in the sense of being inconsistent with target knowledge (see Table 4). The most significant feature of the framework may well be the omissions – their lack of connections between the common mental model of the atom, and the mental models of particles in the states of matter; the lack of linkage between atomic motion and particle arrangements; the lack of focus on interactions between particles; the apparent dichotomisation of energy inputs into those which go to atoms (and are considered to only lead to increased electron motion) and those which heat matter to change overall particle configurations. We would suggest the most noticeable thing about our representation of Swedish students' mental models of the particulate nature of matter is how the conceptual framework is partial and disjointed, so that it has limited value in forming a theoretical basis for explaining the physical and chemical nature of matter - which of course is the prime value of the particle models used by scientists (Taber, 2007). It would seem to be this incomplete and incoherent nature of student thinking that needs to be explained in the Swedish context.

Discussion

The students' notion of immobility of matter in the solid state might be caused by several factors. One of these is an unfortunate choice of words in Swedish for the solid state. *Fast form* does not only mean solid state, since *fast* also has the everyday, non scientific meaning stuck/trapped or fixated. Familiarity with the phenomenon of the solid state at the molar level is also likely to be a key factor that contributes to why the static aspect of the images/models presented to the students are so easily adopted. Yet another explanation might be found when looking at their drawings. The models drawn by the students are the same types of representations found in textbooks and used by teachers. Unfortunately students do not appreciate the highly schematic nature of these teaching models as representations of the scientific models. So the students' descriptions of the atomic model show an oversized nucleus that is perceived as completely immobile while the main emphasis is directed towards electronic movement. The apparent belief that the internal structure of the nucleus is fixed is inconsistent with the more dynamic models used in science, but probably has few *direct* consequences for chemistry learning at this level. However, a belief that the atomic nucleus is completely immobile could contribute to the construal of immobility for matter in the solid state. Clearly an appreciation of molecular motion, whether translational, rotational (in fluid states) or vibrational (in all phases, including the solid state) would imply a mobile nucleus.

Previous research has not highlighted and discussed the immobility of the nucleus as a key feature of students' mental models and clearly further research on this point would be of value. It is possible that this feature has arisen in this study because of some aspect of teaching and learning chemistry specific to the Swedish system (or at least not shared in other countries where similar research has been undertaken). It will be useful to know if similar beliefs can be found in samples of learners from other educational contexts. It is also important not to assume a direction of causality in the findings reported. It may be that a mental model of the atom with a static nucleus leads to an expectation of atoms being stationary in solids – but it is also possible that an assumption of an immobile atom reasonably leads to deducing a stationary nucleus. After all, students who held models of the atom with a stationary nucleus in this study still conceived of *the particles in fluids as moving*: something that might seem to be a logical contradiction.

Future research might explore the 'frame of reference' students are applying when they judge the nucleus immobile. If the atom itself is the fame of reference, then a stationary nucleus does not need to imply an immobile atom - in the same way that considering the Sun stationary *from the frame of reference of the solar system*, is not inconsistent with a belief that the Sun (along with the various bodies orbiting it) is moving *through the galaxy* extremely quickly. If, however, further research suggests that students' notions of a static nucleus are more significant, then this could inform pedagogy in this aspect of chemistry. Introducing movement within the atomic nucleus when teaching the Bohr model might challenge the students' views on which 'parts' are actually moving, and help lead to a sounder model of the different states of matter and changes of state. This would suggest that teachers and textbook writers should put extra emphasis on the nucleus in the Bohr model.

As previously mentioned, the atomic model presented seems to be readily (and somewhat literally) accepted by students, which leads one to believe that a more correct model of the atomic nucleus could just as easily be adopted by students. Diffuse and moving nuclear particles (their wave function could be overlooked until the dual nature of the electron is addressed) might give students a more authentic model, but might perhaps also support a better understanding of particle movement in the different states of matter.

It is considered troubling that the student models (at 16 years of age) show a range of alternative conceptions that have been seen amongst much younger students in other countries (e.g. Renström, Andersson & Marton, 1980). Research into learners' ideas in science is based on the assumption that knowledge of student thinking about topics, and how their mental models evolve in response to teaching, can inform pedagogy and so help teachers develop student thinking towards more scientific models (Taber, 2006a). This programme of research often involves both in-depth studies with small numbers of learners to explore the intricacies and shifts in thinking, and surveys of larger numbers of students to estimate how commonly significant conceptions elicited in the in-depth studies may be held in wider populations (Taber, 2000b). The present research is based on an in-depth study of a modest sized cohort of learners, and further research is indicated to find out if the features of the mental models elicited from these students are widely reflected in the Swedish population.

The origins of the findings reported here are likely to be multi-factorial, including influences that have been recognised to be significant in the learning of younger students elsewhere (the abstract nature of the material, the lack of familiarity with the nature of models etc.) However, this study, especially if the findings can be replicated more widely in the population, raises the question of why in the Swedish context 16 year-olds should hold these conceptions of the particulate nature of matter.

We conjecture that one key factor may be the nature of the national curriculum in Sweden, which sets out aims that are tied to broad age ranges in the school system. This leads to the ‘reintroduction’ of the fundamentals of chemistry at the beginning of upper secondary and university level. The reintroductions reflect a lack of knowledge progression within the subject of chemistry in Swedish schools. The national syllabus and its goals are designed to give each teacher the right of interpretation and freedom to choose at what age the assigned hours are to be used. This leads to major differences in the way the subject is taught, the level of description, evaluations - between schools, between classes and theoretically also between students, since teaching is supposed to be individually based.

> ´at each school and in each class the teacher must interpret the national syllabuses and together with the pupils plan and evaluate teaching on the basis of the pupil’s preconditions, experiences, interests and needs´
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It is therefore impossible for any teacher meeting a new class at the beginning of any level to be confident about the material the students have encountered during previous educational level.

has been found that even with opportunities for applying and consolidating learning, most students need a number of years to overcome the counterintuitive aspects of the basic (i.e. undifferentiated into atoms, molecules etc) particle model (Johnson, 1998). A more specified curriculum, that ensures introduction of the particulate nature of matter to students before year nine (age 15), could contribute to a better knowledge progression for these students. Students should be thoroughly familiar with the basic particle model, including the presence of interactions between particles and the inherent motion of particles, and how these particles are arranged in the different states matter in terms (including vibrational motion in solids), before they can appreciate how heating increases particle energy and leads to changes of temperature (and pressure in gases) and changes of state. Only when this level of understanding is well established, can it be considered robust enough to act as foundations for further learning about particles models (Taber, 2004). Only then will the introduction of molecules and ions, and subatomic particles, provide a coherent differentiation of the basic particle model, and allow meaningful learning about the Bohr model of the atom: which can in turn provide the basis for understanding chemical change, and how this involves different types of particle interactions compared to physical changes such as changes of state (Taber, 2001). Emphasis on the connections between the different models presented and the different contexts in which they are used, would support developing understanding and so contribute to preparing these students for further studies, and making sense of the more intellectually challenging models to come.

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