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Seventh-grade Students' Understanding of Chemical Reactions: Reflections from an Action Research Interview Study

Ingo Eilks
University of Bremen, Bremen, GERMANY

Jens Moellering
Geschwister-Scholl-Gymnasium, Garbsen, and University of Hildesheim, Hildesheim, GERMANY

Nicos Valanides
University of Cyprus, Nicosia, CYPRUS

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This paper discusses seventh-grade students' explanations of dissolution and combustion and also identifies their understanding of the differences between physical and chemical changes. A teaching strategy was initially negotiated within an action research group and this strategy was then employed in teaching seventh-grade students. The teaching approach applied the idea that discrete particle changes can be used to differentiate chemical reactions from simple physical changes. Data were collected by an action research group teacher who conducted interviews with dyads of students from different chemistry classrooms. The interviews were transcribed, subsequently analyzed and evaluated in co-operation with researchers from the university. The main mistakes and alternative conceptions that have been identified are discussed. Further, some implications for developing appropriate teaching strategies and curriculum materials are also summarized.

Keywords: Chemical Reactions, Students' Conceptions, Action Research

INTRODUCTION

Explaining macroscopic phenomena on the particulate level is considered an essential idea of modern science and science teaching (Johnstone, 1991). Nevertheless, science education research (Novick & Nussbaum, 1978; Pfundt, 1982) indicates that this is not an easy task to achieve. A large variety of conceptual gaps in students' understanding of the particulate level (Andersson, 1990; Garnett, Garnett & Hackling, 1995) or related issues, such as the concept of matter (Krnel, Watson & Glazar, 1998), have been also identified.

In science classrooms in Germany, learning about the particulate nature of matter typically begins in early secondary chemistry education. The first teaching approach towards the particulate level in most of Germany's 16 States takes place in 6th or 7th grade chemistry (age range 11-13), although each of the States uses a different syllabus.

Six years ago, a group of researchers and practitioners started a project of Participatory Action Research in chemical education (Eilks & Ralle, 2002; Eilks, 2002). The project aims at developing 'New ways towards the particle concept' (Eilks & Moellering, 2001). The central objective of the project is the design and

Correspondence to: Ingo Eilks, Prof. Dr.,Chemistry Education, University of Bremen, Department of Biology and Chemistry, Institute for Science Education (IDN), Leobener Str. NW 2, 28334 Bremen, Germany
E-mail: ingo.eilks@uni-bremen.de

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Table 1. Distinction between chemical and physical changes

Level of Change	Physical Change	Chemical Change
Macroscopic	Changes in the form a specific kind of matter appears in or its localisation related to other substances	Changes of specific kind(s) of matter into different kinds of matter
Sub-microscopic (particulate)	Change in the arrangement of discrete particles of a specific kind of matter or in their localisation related to discrete particles of other substances	Changes in the discrete particles of a substance or substances into discrete particles of a different substance or substances
Examples	Changes in the state of matter, dissolution, diffusion	Chemical reactions

development of innovative and effective teaching strategies dealing with the particulate nature of matter in lower secondary chemistry teaching. This approach targets the development of lesson plans, the application of cooperative learning strategies, and the integration of new media into teaching and learning.

The development, testing, and revision of teaching strategies follow the pattern of Participatory Action Research and are accompanied by diverse approaches in evaluating their effectiveness (Eilks & Ralle, 2002; Eilks 2002). The evaluation focuses on students' achievement and understanding, including the acceptance and feasibility of the specific teaching strategies, from both the students' and the teachers' perspectives (e.g. Eilks, 2005). This evaluation is partly conducted by teachers from the action research group in small scale action research studies. This approach promises to contribute towards 1) optimizing teachers' practices and 2) fostering teachers' competencies in evaluating their students' learning and understanding, thereby contributing to their professional development. Similar projects in the past exemplified the potential of different forms of action research in evaluating students' understanding, initiating change, and improving teachers' professional skills (Scott & Driver, 1998; Valanides, Nicolaidou & Eilks, 2003; Gilbert & Newberry, 2004).

In this paper, an interview study focusing the evaluation of students' ability to differentiate between physical and chemical changes is described. The distinction between physical and chemical changes in matter follows the interpretation discussed by Hesse and Anderson (1992) or Eilks, Leerhoff, and Moellering (2002). From this perspective, physical changes are changes (i) in the appearance of matter on the macroscopic level and (ii) a rearrangement of particles on the sub-microscopic (particulate) level, whereas chemical changes constitute (i) changes in matter itself on the macroscopic level and (ii) changes in discrete particles on the particulate level, as indicated in Table 1.

RELATED RESEARCH

During the last twenty-five years, research has extensively investigated students' understanding and alternative conceptions in science, including their underlying implications for the teaching and learning of science. Various review studies tried to present an integrated picture of findings related to characterising matter and its properties.

One of the first concepts introduced in early chemistry teaching is usually the idea of matter[1] and its properties. The concept of matter is of central importance to the particulate nature of matter and related issues (Andersson, 1990; Garnett et al., 1995; Krnel et al., 1998). Krnel et al. (1998) reviewed related research and outlined aspects of students' insufficient understanding of the concept of matter and its properties, prior to introducing chemical changes. For example, in students' thinking there is no clear distinction between matter and other things not belonging to the category, such as forms of energy or feelings. Other categories, like mass or expansion, which facilitate the distinction between matter and forms of energy, are not always available or are not correctly applied (Stavy, 1990).

Similar misunderstandings also arise from an insufficiently developed 'chemical' understanding when dealing with the concept of properties. Sometimes, students cannot distinguish clearly between the use of relevant properties describing matter and those relating to the form or size of objects. For example, students use temperature (an intensive property) or volume (an extensive property) to characterise matter itself (Krnel et al., 1998; Solomonidou & Stavridou, 2000).

Mistakes and communication problems between teachers and learners also arise from semantic problems in the use of names and notions (Krnel et al., 1998; Johnson, 2000). Names and notions are usually used in their everyday or trivial way. In most cases, such usages are not identical to the scientific meaning of the word or term. For example, the German word 'Stoff' has different meanings, such as cloth, stuff, subject matter, and in chemistry: matter or substance.

[1] The term matter here is used as translation of the German term 'Stoff'. Other terms, such as 'Material' or 'Substanz' are sometimes used. Distinctions between matter and substance from English cannot be easily transferred to German language use.

Several other problems have been also identified in characterising the properties of matter and chemical change which are caused by misinterpretations of the relationship between matter and its particles. The properties of a substance are sometimes considered as identical to the properties of the particles themselves, without taking into consideration the important differences between the macroscopic and the particulate level (Lee, Eichinger, Anderson, Berkheimer & Blakeslee, 1993; Johnson, 1998).

Chemical and Physical Changes

Chemical reactions in most cases are initially introduced on a phenomenological level. Several researchers (Pfundt, 1982; Meheut, Saltiel, & Tiberghien, 1985; Johnson, 2000) stated that students do not often consider chemical reactions as a complete transformation of the matter itself, but only as a change in its appearance or as a change in the state of matter. Consequently, students tend to make no clear distinctions between physical and chemical changes (BouJaoude, 1991). Chemical reactions are often considered as a process of 'mixing' the initial substances, because the relationship between the macroscopic world and the particulate level of matter is not clearly understood (Johnstone, 1991; Johnson, 2002). Thus, the products of chemical reactions are often considered as mixtures of the initial substances, and their properties as a combination of the properties of the initial substances (Meheut et al., 1985; Ebenezer & Erickson, 1996).

Students usually believe changes on the particulate level occur in the same fashion as those on the macroscopic level (Lee et al. 1993, Andersson, 1990). Chemical reactions are sometimes introduced as a rearrangement of atoms without making it clear that this automatically implies changes in the discrete particles, and their constituents (atoms) as well. This gap in understanding usually relates to the Dalton understanding of chemical change which is quite often used in German textbooks. However, a correct understanding of chemical models is not always presented to the students simultaneously by their textbooks (Eilks et al., 2002). If students conceptualize the rearrangement of atoms, but do not associate any further changes connected with the atoms or the sub-atomic particles that constitute them, the danger exists that the students may view that the new substance is 'just' a mixture of the initial substances.

Reflection upon the nature of models and their strengths and limitations may help students to understand the differences between Dalton's model and their experiences from the macroscopic world when mixing things. Unfortunately, students are not always aware of the correct use of models. They often neglect either the fact that different ideas and concepts have to be applied within models or that models are not an exact replication of reality (Grosslight, Jay, Unger, & Smith, 1991; Lee et al., 1993; Taber, 2001).

Several researchers (Ahtee & Varjola, 1998; Johnson, 2002) suggested that misunderstandings may be reduced by developing a clear understanding on the particulate level in the early stages of schooling. This, however, can only happen if the particulate interpretation of chemical changes is introduced quite early, if this concept is comprehensible and if a clear distinction between the macroscopic and the microscopic levels is constructed (Johnson, 2002). Delayed introduction of the particulate nature of matter may consolidate students' naïve conceptions about physical and chemical changes, thus the particulate explanation may not become an equally-valued basis for students' interpretation of phenomena. In such a case, students will still attempt to explain most phenomena on the macroscopic level without considering the particle level (Stavridou & Solomonidou, 1998).

However, if a particle concept is introduced quite early in science teaching, we have to carefully investigate which explanation for chemical reactions on the particle level should be used. In most cases, the first particle model to be introduced in chemistry teaching is a model of discrete particles. Hesse and Anderson (1992) outlined that an understanding of chemical reactions must be introduced as a change in the constituent discrete particles of the initial substances (Andersson, 1986; Gomez, Pozo & Sanz, 1995). This strategy promises to foster better understanding of the distinctions between chemical reactions and physical changes. Taber (2001) also argues that it would be more productive to start thinking in terms of discrete particles in chemistry education rather than on the level of atoms, provided, of course, that changes in the discrete particles are not neglected. The distinction between these two levels is presented in table 2.

Usually in German chemistry classrooms, different models are progressively introduced. Introductory chemistry teaching starts with a model of particles. Later, in most cases, a simple model of atoms is introduced following the historical ideas of Dalton, and chemical reactions are explained as a rearrangement of atoms. In most cases, the concepts of atomic structure and bonding are introduced much later during grade nine.

Unfortunately, no clear distinction is made in some textbooks between atoms and the discrete particles of a substance (Eilks et al., 2002). Even when the concept of atoms is accompanied by a distinction between atoms and discrete particles, the distinction is not clearly understood among younger students. Both models use spheres to represent particles. A mixture of different

Table 2. Levels of understanding from macro- to submicroscopic

Macroscopic level (The phenomenological world)	The 'out-of-reach world'	Things outside the earth that can be seen and measured (e. g. objects in astronomy, although they cannot be reached).
	The macroscopic world	Tangible things from the macroscopic world around us that can be seen and characterized with our eyes, ears, etc.
	The microscopic world	Things from the macroscopic world that are too small to be seen, but which can still be characterized using microscopes and other measuring tools.
Sub-microscopic level (The 'world' of the particulate nature of matter)	The level of discrete particles	The level of particles and structures which are discrete, e. g. molecules, atoms in inert gases, or structures in solid bodies
	The level of atoms	The level of atoms building up discrete particles and structures
	The level of atomic structure	The level of sub-atomic building units (electrons, neutrons, protons) responsible for bonding and structure

models often constitutes a source of confusion (Carr, 1984). The application of a model of atoms without relating them to the level of discrete particles usually leads to an understanding of chemical reactions as mixtures of the initial substances (Ben-Zvi, Eylon & Silberstein, 1987; Garnett et al., 1995; Ebenezer & Erickson, 1996).

Understanding combustion in early chemistry teaching

Oxidation and combustion in early chemistry lessons constitute an area where similar problems have been investigated and described. These problems occur frequently, especially when oxidation and combustion are closely connected to everyday life experiences. Personal experience usually constitutes a main source of alternative explanations and conceptions among pupils (Pfundt, 1982). Naïve interpretations of everyday phenomena usually give rise to alternative conceptions where students believe that all chemical reactions are irreversible, that combustion is usually associated with destruction or disappearance of matter and its mass, or that combustion always produces gaseous compounds (BouJaoude, 1991; Nakhleh, 1992).

One possible explanation stems from younger pupils' belief that 1) matter, 2) mass as a necessary attribute of this matter and 3) the principle of conservation of mass are not interconnected. Thus, some students may think that matter exists without having any mass and, consequently, that chemical changes result in the loss of mass or in the creation of something from nothing (Stavy, 1990). Gomez et al. (1995) stated that the principle of the conservation of mass is more frequently accepted for physical changes rather than for chemical reactions. These problems are not restricted to early chemistry learning, but they often occur among older students who have been taught chemistry for many years (Valanides et al., 2003).

Understanding dissolution in early chemistry teaching

Physical processes themselves are often not correctly understood, and several research studies investigated students' understanding of the states of matter (Andersson, 1990) and the processes of dissolution and distillation (Johnson, 1998; Valanides, 2000a, 2000b). For example, dissolution is often viewed as a loss of substance or mass, because it is considered to be a process resembling evaporation (Johnston & Scott, 1991; Lee et al., 1993; Krnel et al., 1998). Dissolution is also related to misconceptions at the particle level, because students believe either that similar changes also occur at the particle level (Valanides, 2000a, 2000b) or that the sub-microscopic particles become lighter (Johnston & Scott, 1991). Similar conceptions are also connected to changes in the state of matter (Valanides, 2000b). These ideas occur especially frequently if the process of dissolution is not clearly separated from the process of changes in the state of matter. Thus, dissolution is sometimes considered as melting of the dissolved substance (Lee et al., 1993; Ebenezer & Erickson, 1996; Valanides 2000a).

Seventh-grade Students' Understanding of Chemical Reactions

Initial Issues Related to a Revised Teaching Strategy

Practicing teachers repeatedly reported that they faced problems when teaching the particulate nature of matter, and research confirmed the persistence of these problems. In Germany, various historical models are generally used as guidelines for teaching the particulate nature of matter. But these models are often not discussed with sufficient care. Students are not usually motivated during the lessons or may face difficulties in correctly conceptualizing the use of the respective models (Andersson, 1986). Analysis of German textbooks also indicated (Eilks, et al., 2002) that even common teaching concepts represented in textbooks are sometimes not consistently or clearly differentiated from the perspective of using different models. Unfortunately, some of the inconsistencies in chemistry textbooks resemble those reported in the literature concerning students' inattentiveness in model use (Eilks, et al., 2002). Some textbooks seem to perpetuate common misconceptions that are spread among the students and create even more confusion in them (Eilks & Moellering, 2001; Eilks, 2003a).

Thus, a project of Participatory Action Research (Eilks & Ralle, 2002; Eilks, 2002) in chemistry education was initiated about seven years ago. The project developed and investigated the effectiveness of different teaching approaches concerning the particle concept. The project followed a cyclical, step-by-step development of teaching strategies and materials that should be compatible with students' understanding and learning capabilities. It also invested in recent teaching methods, e.g., use of new media or cooperative learning.

The action research group decided to develop a new model approach for the particle concept which is consistent in and of itself. The group would follow the new model through the different stages of chemistry education in hopes avoiding breaks in students' learning caused by rapid switching from one chemistry model to another. The new model should not only be internally coherent, but also scientifically acceptable and compatible with students' learning capabilities as well. Similar ideas had been proposed by de Vos and Verdonk (1995). But their concept was only worked out for the first step. The objective was to design and develop a coherent and well-tuned didactical sequence and specific guidelines for effectively teaching the particulate nature of matter in lower secondary science. Their main guiding principle was to coordinate the systematic development of students' knowledge over different stages of their education without discrepancies from the basic model that would be initially introduced. Thus, the objective was to avoid difficulties arising from the progressive adoption of new models that played a role in the history of science. The progressive introduction of new models, following their historical development necessarily, demands relevant 'conceptual changes' in students' knowledge rather than a simple enrichment in their existing knowledge structures.

For example, if a model is introduced where spheres represent discrete particles (such as molecules, ions (both mono- and multi-atomic), or atoms in inert gases and metals), then students at a later stage often face lasting difficulties in distinguishing among these particles and their constituent entities (the single atoms that are also usually represented by spheres in different models). Teachers are usually, but not always, able to make a clear distinction between discrete particles and atoms, however their students often are not able to do so and therefore face many difficulties. This situation does not encourage pupils' motivation to be cognitively engaged in learning chemistry.

This approach has implications for students' understanding of chemical reactions. Chemical reactions are introduced in some German curricula as a rearrangement of particles. For some of these concepts, even textbooks do not introduce a clear distinction between the level of simple (discrete) particles and the level of atoms, as discussed in table 2 (Eilks et al., 2002). Therefore, students attempt to rearrange simple discrete particles to explain chemical reactions. Consequently, they may conceptualize chemical reactions as a kind of dissolution or diffusion (or just mixing) which, however, are physical processes and not chemical changes.

The application of the sphere-model for discrete particles does not facilitate the explanation of changes in substances during chemical reactions, as shown in figure 1. The model does not allow the composition of a pure substance as the product of a reaction of two initial substances, because such a product has to be built up by identical spheres representing the particles of the product. The formation of these spheres is not possible within the model. Additionally, the reaction from one initial substance into two or more products is not possible (in figure 1 the reverse reaction). In this case, we should have one kind of identical spheres at the beginning, and two or more kinds of particles after the completion of the reaction. This cannot be explained by any kind of 'rearrangement'.

The participants in this action research group strongly believe that there is no need to introduce a 'model of discrete particles to be represented by spheres' as suggested by most German textbooks. The group preferred the introduction of a 'model consisting of discrete particles of different form and size'. The group agreed that this approach will:

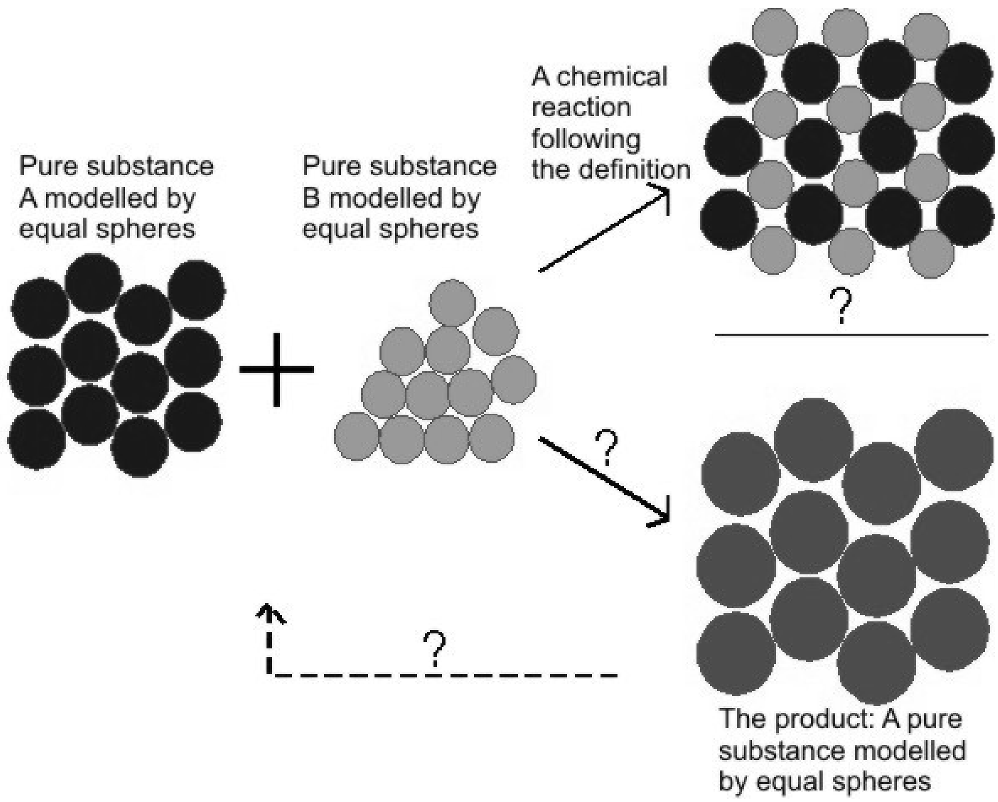

Figure 1. Problems in explaining chemical reactions based on a simple model of spheres representing discrete particles

- Allow an understanding of chemical reactions as a change from the constituting particles of specific kind(s) of matter into the constituting particles of different kinds of matter. A chemical reaction on the level of simple particles should be connected to the idea that these particles undergo changes leading to the formation of totally different particles of the new substance or substances (e.g., Hesse & Anderson, 1992).
- Reduce the possibility of the occurrence of misunderstandings concerning the distinction between the levels of discrete particles themselves and of their constituting entities, i.e., the level of atoms.
- Be helpful in facilitating the later introduction of different types of discrete particles represented by this model (molecules, ions, or atoms of inert gases).
- Allow dealing with the same model across the whole chemistry curriculum and facilitate a consistent continuation to the level of atoms and sub-atomic particles as the building units of the discrete particles that will be initially introduced. Thus, only one model will be introduced that will be developed step by step while looking more and more deeply into the sub-microscopic structures.

For the purpose of the present study, some of the essential units of chemistry teaching at the first year in Germany seem to be relevant. The course regularly consists of units related to matter and its properties, states of matter, dissolution, methods of separating matter, (e.g., filtration, distillation, or extraction) and initial understanding of the concept of chemical reactions. The concept of chemical reactions is introduced primarily using examples of combustion and oxidation.

The teachers structured all the units using experiments and applications from everyday life, and an attempt is made to connect macroscopic explanations with the sub-microscopic level. Using this approach, experiments are usually conducted by students themselves as hands-on activities, which is commonly accepted as a main goal of chemistry teaching in Germany. Nevertheless, teaching is commonly built around teacher-centered, didactic instruction (informally called "chalk and talk" methodology by many English-speaking teachers) with low levels of direct student participation and pupil-centered activity (Fischer, Klemm, Leutner, Sumfleth, Tiemann, & Wirth, 2005).

In the negotiated teaching strategy, explanations on the sub-microscopic level are based on a simple concept of discrete particles, as suggested by Taber (2001). Emphasis is placed on more frequently explaining school chemistry from the level of discrete particles than from the level of atoms. All explanations on the sub-microscopic level are worked out using multimedia-based learning environments (Eilks & Moellering, 2001).

These multimedia-based environments offer different learning sequences, including video clips of experiments that were previously conducted in the classroom, theoretical explanations, and animated illustrations at the particle level. Chemical reactions are introduced as changes of discrete particles (e.g., Hesse & Anderson, 1992), and these changes are later explained as a re-arrangement of the building blocks of these particles, e.g. atoms and their constituent sub-atomic particles, into new discrete particles forming the new substance or substances. This second step had not been discussed in detail in most of the learning groups prior to this study. In those few groups where such a discussion took place, only the initial idea that these discrete particles are built up from single atoms was introduced.

BACKGROUND AND METHOD

The process of developing teaching materials and strategies via Participatory Action Research is accompanied by several different kinds of evaluation. Some aspects are evaluated in broader case studies by the participating researcher(s) (e. g. Eilks 2005), while other aspects are evaluated through smaller-scale case studies conducted by the participating teachers (e. g. Witteck & Eilks, 2006). The main purpose of these studies is to gain insights into possible ways for further improvement in a new cycle of development. This also more thoroughly involves the participating teachers in the assessment processes within the action research network, and familiarizes them with the evaluation and research processes.

The present study attempted to investigate 1) whether students taught using this approach were able to correctly conceptualize aspects of the particle concept, and 2) whether they could explain phenomena using correctly the particle level. It was thus possible to examine whether students' preexisting conceptions continued to be present in their arguments, and also to determine both the kind of preconceptions present and the possible reasons for their persistence after instruction. We could also examine whether and how this kind of action research was beneficial for developing a cooperative curriculum project within the Participatory Action Research paradigm.

This paper describes an interview study carried out by an action research teacher using seventh-grade students from four different grammar schools (age range 12-13), who had been taught by other teachers in the same action research group. The lessons addressed the particle concept, respective explanations of the states of matter and their changes, and solubility. They took place about 6 months prior to the collection of data, but the lessons concerning chemical reactions took place in the middle of this teaching sequence (about 3 months prior to the collection of data). Volunteer students from each group were selected for the interviews. From the volunteers, the respective teachers selected two pairs of students, one pair characterised as being 'high achievers' and the other as 'low achievers'.

The decision to conduct interviews with pairs of students rather than with individuals alleviated teachers' concerns that students, especially "low achievers", might 1) provide only short, superficial answers to the interview questions and 2) might possibly feel uncomfortable in the interview situation. The teachers expected that the necessary interaction between the students in each pair might make the interview more interesting and frank and also avoid students' feelings of isolation in the assessment situation.

Interviews were conducted with 8 pairs of students. They followed interview guidelines and were conducted as semi-structured, content-focused interviews. The interview guidelines were initially suggested by the interviewer, but they were extensively discussed and modified within the research group. They were also pre-tested by the interviewer with students from his own learning group and modified accordingly. The key

Table 3. Features of the interview guide*

Q1:	What do you know about matter and its structure?
Q2:	Think about wood burning in a fireplace. Describe and explain what will happen!
q2.1:	If there is an argument based only on the macroscopic level: Which other characteristics of this phenomenon do you know about?
q2.2:	Imagine you are able to retain all products of a reaction. How do you consider their weight together compared with the weight of all the initial substances?
Q3:	Think about a spoon full of salt, which is put into a glass of water. Describe and explain what will happen!
q3.1:	Which substances will be in the glass at the end of the process?
q3.2:	Explain the phrase 'Water has become salty'.
Q4:	How do we recognise chemical reactions?
q4.1:	If a characterisation is based only on the macroscopic level: Which other characteristics of chemical reactions do you know about?
q4.2:	If there is a characterisation based only on the particulate level: Which other characteristics of chemical reactions do you know about?

* Q: Key question of the interview; q: Supplementary aspects to be introduced if not mentioned by the students

features and supplementary features of the interview guide are given in table 3.

Each interview lasted for about 15 minutes. The interviews were audio-taped, subsequently transcribed and then analyzed in cooperation with researchers from the university. Evaluation was guided by ideas of qualitative content analysis (Mayring, 2000) and addressed the following key questions which were set forward by the research group:

- Do students consider the particulate level in their explanations when they are asked open-ended questions concerning macroscopic phenomena without any prompts from the interviewer?
- Do students express connections between the macroscopic and the particulate level in their argumentation? Is this connection meaningful and correct initially or only after any prompts?
- Which aspects/concepts from the particulate level are correctly applied and which commonly-held misconceptions appear in students' argumentation?

Finally, both the data and results were discussed within the action research in an attempt to address the following questions:

- To what extent can such small-scale action research studies be used to evaluate students' learning?
- What are the implications of small-scale research studies on curriculum development within action research projects?
- What are the effects, if any, of the present study on the members of the participatory action research group?

RESULTS AND DISCUSSION

Students' Knowledge about the Particle Level

Table 4 shows an overview of students' ideas about the particulate level of matter. All students, including the low-achieving ones, were able to recall their knowledge about the particulate level. Among the low-achieving students, recall of relevant information concerned both stating that matter is made up of particles and giving several details, e.g. aspects from explaining changes in the state of matter. High-achieving students also made reference, without any prompting, to the relationship between the particles themselves and the atoms and to the movement of particles and their changes during chemical reactions. Only some of the high-achieving students made reference to the empty spaces between the particles or the relationships and differences between macroscopic and sub-microscopic changes.

Evidence in table 4 also indicates that students did not really comprehend all their memorized knowledge. An excerpt from the discussion between two low-achieving students concerning mass conservation exemplifies this situation:

I: But what about the mass?

2L2: I believe it becomes smaller.

2L1: No, the mass is not getting smaller, I believe. I read in a book that after a chemical reaction there is just as much as before and that only colour, shape, and so on changed a bit.

I: Do you believe what you read?

2L1: Well, actually only a little bit. I cannot imagine that ... well, that everything consists of particles. I have asked my mother and my father, whether I also consist of such particles. And then they said yes. I can´t really imagine that.

I: Student 2 – What do you think?

2L2: I am not sure. I cannot imagine that either. When there is oxygen in the room … now and then this chemical reaction. I always think that it becomes smaller, because the oxygen is somehow gone, but also creates a new form. Then I don´t know if the mass stays the same.

(Learning group 2, students achievement considered by the teacher as regularly below the average, I: interviewer, 2L1: student 1, 2L2: student 2)

High-achieving students could easily explain states of matter and their respective changes as indicated in the following excerpt:

I: What do you know about the structure of matter?

2H1: That it consists of particles.

2H2: That a substance always consists of small particles, no matter what the substance is, and that the particles of a substance can be transformed to different particles during a chemical reaction. […] A substance can also exist in different states of matter (liquid, solid, or gaseous), and the particles stay the same […]

I: What else do you know about the small particles?

2H1: They are responsible for the states of matter. When a substance is in liquid form, then the particles are a little bit further apart from one another than in the solid state, and when they are in solid state, then particles move only a little bit and are very close to each other. In gaseous state, particles are much further apart from each other, all mixed up, and flying around.

(Learning group 2, students achievement considered by the teacher as regularly above the average, I: interviewer,2H1: student 1, 2H2: student 2)

Table 4. Overview of the students' answers*

	1L	1H	2L	2H	3L	3H	4L	4H
What do you know about the structure of matter?								
All substances are formed of particles. Particles are different for different substances.	X	X	X	X	X	X	X	X
States of matter are related to the movement and the distance of particles.	X	X		X	X	X	X	X
Particles are in continuous motion.				X	X		X	X
Matter can change through chemical reactions.	X			X		X	X	
The particles are very small and invisible. They can only 'be made visible' by Scanning Tunneling Microscopy.	X			X				
What happens if wood burns in a fire place?								
Burning of wood is a chemical reaction.	X	X	X	X	X	X	X	X
New substances are formed.	X		X	X	X		X	
Wood reacts with oxygen forming 'wood oxide' (or carbon dioxide, etc.).	X			X	X	X	X	
New substances can be identified due to their properties.	X		X	X		X		
Particles from wood change into different particles.	X	X	X	X		(I)		X
Total mass of the products:								
is bigger.	X	X						
equals the mass of reactants.	(I)			X	(D)	(D)	X	X
is smaller.			X		X	X		
What happens if a spoon of salt is put into a glass of water?								
Dissolution of salt in water is a physical change.	(I)	X	X	X	(I)	X	(I)	X
The particles do not change. Particles are still there, But, the particles are too small to be seen			X	X		X		X
The particles move away from each other. They are distributed between the water particles.		X	X	X	(I)	X		X
The movement of water particles is the driving force for dissolution.				X		X		X
Dissolution of salt in water is a chemical reaction. A new substance is formed. Salt and water particles combine into new particles.	X						X	
How do you explain the phrase 'the water became salty"?								
A new substance is formed.	X						X	
The salt particles are distributed within the water particles.		X	X	X	X	X		X
How do we recognize a chemical reaction?								
Two initial substances form *one* new substance. The new substance can be recognized by its new properties. (Cases were more than one product is formed were not described.)	X	X	X	X	X	X	X	X
Particles change. Initial particles combine and form new particles with new properties.	X	(I)	(I)	X		(I)	X	X
During chemical reactions thermal energy is set free to the environment through an exothermic reaction.	X	X		X		X		X
Chemical change of matter always is accompanied by energy transformations.				X		X		
What happens if a cake is baked in an oven?								
Baking a cake is a chemical reaction. New substances are formed which can be characterized by their new properties.	X	(D)	X	X		(D)	(D)	X
A change in the particles takes place.	X	(D)	X	X		(D)	(I)	X
Baking a cake is a physical change. The only change is a change in the state of matter (from liquid to solid).		X			X	X	X	

* 1L means learning group 1, lower-achieving students; X = Ideas mentioned by the students, (I) = Ideas mentioned after an additional prompt by the interviewer, (D) = Change in the ideas mentioned after a short discussion without any prompt from the interviewer)

Some of the low-achieving students also provided correct explanations related to a basic understanding of the differences among the states of matter in terms of their constituent particles:

4L1: Different substances can exist in a liquid, gaseous or solid state. Each substance consists of small particles and, depending on the state of matter, the particles are further apart from each other and move faster. And if a substance gets warmer, then its particles move faster and thus expansion occurs.

(L*earning group 4, students achievement considered by the teacher as regularly below the average, I: interviewer, 4L1: student 1,4L2: student 2*).

Chemical Reactions in General

All students began describing chemical reactions as a change of properties. In most cases, this was explained by the formation of a new substance with totally new properties different from the initial substance. Students studied chemical reactions starting with the caramelization and carbonization of sugar, but nearly all of them described chemical reactions as a means of synthesis. For example, they considered a chemical reaction to be a reaction between *two* initial substances forming *one* product ($A + B \rightarrow C$) without any other possibilities, such as $A \rightarrow B$, $A \rightarrow B + C$, or $A + B \rightarrow B + C$.

Most of the students tried to explain chemical reactions in terms of the particulate matter. High-achieving students explicitly stated that a change of the constituent particles always occurs in a chemical reaction. In all these cases, the correct connection between both levels of explanation was correctly stated:

2H1: The small particles change.

2H2: The substance does not remain as it used to be. It looks -well- totally different and it has different properties.

I: What is the reason?

2H2: The small particles from different substances combine and form a new substance. They look different then.

I: And what are the results?

2H2: A molecule.

I: And do the particles then still exist?

2H1: Yes, the particles are still the same, but they are linked with each other. And in a physical process, they are also the same, but not linked to each other, only mixed.

*(Le*arning *group 2, students achievement considered by the teacher as regularly above the average interview 3, I: interviewer, 2H1: student 1, 2H2: student 2).*

Additionally, in some cases correct explanations were given which included the relationship between the level of discrete particles and their constituent atoms:

I: And what about the particles?

2H1: They don´t change.

I: Don´t change?

2H1: Sure, the particles change, but the atoms don´t. So if you have oxygen, then it always stays an oxygen atom. It´s just that the particles can be put together differently.

2H2: For example, if one had oxygen and magnesium, … No, if one had oxygen atoms and carbon atoms, they combine to form particles of carbon dioxide.

I: So, the atoms don´t change?

2H1: No, but the composition of the particles changes.

(*Learning group 2, students achievement considered by the teacher as regularly above the average, I: interviewer, 2H1: student 1, 2H2: student 2*)

Low-achieving students talked about the particle level only after prompts from the interviewer. Some of them tried to refer to the particle level when making the distinction between chemical reactions and physical processes. In the following excerpt, two low-achieving students considered baking a cake a physical process, but then changed their ideas and correctly considered the baking process a chemical reaction.

4L1: I´d say it´s a physical process. Only the state of matter changes, it turns from liquid to a solid. The taste stays the same.

4L2: The properties of the substance actually don´t change.

4L1: Maybe, it is not a chemical reaction then.

I: You have to prove that.

4L1: There are the initial substances, e.g., milk, eggs, sugar and so on, plus activating energy that would be the heat from the oven. Well, and out of that it becomes a substance, which includes the initial substances together, but is something totally different. So that would be a chemical reaction.

I: How could you notice it?

4L2: Maybe through the little particles, if they changed. If yes, then it is a chemical reaction. If not, then it is a physical process.

(Learning group *4, students achievement considered by the teacher as regularly below the average, I: interviewer, 4L1: student 1,4LS2: student 2).*

In some cases, students also gave wrong explanations. For example, in one interview with two low-achieving students, the pupils stated that properties change because chemical reactions are always related to some kind of combustion. In another interview, low-achieving students mentioned that chemical reactions are always not reversible. In almost every interview, transformations of energy during a chemical reaction were mentioned and a lot of correct ideas were presented, but students considered all reactions to be exothermic. They also stated that activating energy was always necessary, and that the initial substances should be heated or ignited for any chemical reaction to occur. Students´ discussions and ideas resemble those discussed by Boo (1998).

Dissolving Salt in Water

All high-achieving students except for one, provided a correct explanation of the process of dissolving salt in water and also made correct reference to the particulate level.

I: Describe the process when a spoon of salt is put into water.

2H1: At first, there is a small hill of salt, when it is put into water. And when one accelerates the process, for example, by shaking the vessel, then they mixed up, that is, the salt mixes with the water. And one cannot see the salt particles anymore, because they spread out into the water. And one only can taste the salty water. The process is similar to dissolving sugar in tea. Again, you don´t see the sugar anymore, you can only taste that the tea is sweet.

I: And why can´t we see the sugar or its particles anymore?

2H1. Because it dissolved.

I: Then the particles are gone?

2H1: No, they aren´t gone.

2H2: They still exist.

2H1: They exist.

I: But what has happened to them, because you said they dissolved?

2H2: But they are still there.

2H1: Yes, they are still there. If one can taste, they are still there of course.

I: Have the particles been changed somehow?

2H1: No, they have only spread out.

(Learning group 2, students achievement considered by the teacher as regularly above the average, I: interviewer, 2H1: student 1, 2H2: student 2)

Some low-achieving achieving students also offered good explanations for the process of dissolving salt in water:

2L1: Well, the salt dissolves slowly, because the particles of water are in motion all the time, and then they shove in between the salt particles. And then it´s dissolved slowly. … until all the salt is finally dissolved in the water.

(Learning group *2, students achievement considered by the teacher as regularly below the average, I: interviewer, 2L1: student 1, 2L2: student 2)*

Some low-achieving students were not able to correctly explain dissolution on the particle level. They expressed a lot of doubts and mixed several concepts together. Two major misunderstandings were prevalent. 1) The students classified dissolution as a chemical reaction or 2) they confused the understanding of dissolution with melting. In any case, they considered the dissolution of salt in water to be a chemical reaction and stated that the particles combine into "salt-water" particles. It is wrong to consider "salt-water" being a new substance. But, if considering this salt-water to be a new substance, the concept was applied correctly. This has to be connected to the formation of a new kind of particles. In the second excerpt, the student's explanations do not seem to clearly distinguish between the macroscopic and the sub-microscopic level. The students argue that the particles are linked together and that the water takes over the taste of salt. It seems that students were also unable to distinguish between the macroscopic and the sub-microscopic levels when explaining dissolution and that they transferred ideas from melting. The students thought that the salt crystals became smaller and could not be seen anymore, because they melted and therefore turned into a liquid.

I: A spoon of salt is put into water. Describe what happens.

1L1: A chemical reaction will occur.

I: Describe the process!

1L1: Well, when you put salt into water, it dissolves. That means its pieces become smaller. And finally it completely dissolves into the water.

I: What dissolves?

1L2: The salt dissolves.

I: How can you explain this?

1L1: The water particles react with the small salt particles. [...]

1L2: No, I actually believe that dissolution is a physical process. During chemical reactions, something is always burned […]. That´s not the case for a physical process. The smell stays and the particles stay the same.

I: Now you said that it is a physical process, but where did the salt go?

1L2: Maybe the state of matter changed or the pieces became so little that one cannot see them anymore. [...]

(Learning group 1, students achievement considered by the teacher as regularly below the average, I: interviewer, 1L1: student 1, 1L2: student 2)

In another group:

4L2: The salt is put into water and the small particles of salt and water combine. Through this the salt dissolves. And together it becomes a different mixture or substance. [...]

I: And where did the salt crystals go?

4L1: In the water.

I: But they cannot be seen anymore.

4L2: They turn from the solid to the liquid state of matter.

I: Then what does the statement 'water becomes salty' mean?

4L1: Well, salt is salty. Water doesn´t taste like anything really and when salt is added, then the salt crystals are taken apart into such little particles that they link with the water particles. And the water just takes over the taste of the salt particles.

(Learning group 4, students achievement considered by the teacher as regularly *below the average, I: interviewer, 4L1: student 1, 4L2: student 2).*

The Combustion of Wood in a Fireplace and the Principle of Mass Conservation

In all cases, combustion was classified as a chemical reaction. Among the low-achieving students, the explanation started at the phenomenological level and students did not make any reference to the particulate level without being prompted to do so. The high-achieving students started from the phenomenological level and progressively provided explanations based on the particulate level without any further comments from the interviewer, as can be seen from the following excerpt:

I: Wood is burning in a fireplace. What is happening?

1H1: A chemical reaction, I guess. When it´s burning, then it is a chemical reaction, because then the fire needs oxygen.

1H2: It could be explained as follows: Wood and oxygen are actually combined and thus 'wood-oxide' or something like that is formed […] I also think that a chemical reaction takes place, because the particles change while wood is burning. And after it is totally burned, the wood looks entirely different and has a quite different appearance. It also smells differently and, well, the particles themselves have been transformed.

(Learning group 1, students achievement considered by the teacher as regularly above the average, I: interviewer, 1H1: student 1, 1H2: student 2)

The principle of the conservation of mass proved to be difficult for both the low- and high-achieving students. Some of them were able to mention the principle of conservation of mass but did not really accept its consequences.

I: How heavy are the resulting products in comparison *with* the initial substances?

2L1: I would guess that the mass is less.

2L2: It stays the same, if wood is burned in fire. Well, it stays as much as it was at the beginning, but it becomes crumbly. And then it changes to a black color.

I: But what about the mass?

2L2: I believe it becomes smaller.

2L1: No, the mass is not getting smaller, I believe. I have read in a book that, after a chemical reaction, there is just as much as before. Only that color, shape and so on changed a bit.

I: Do you believe in what you have read?

2L1: Well, actually only a little bit. I cannot imagine that.

(Learning group 2, students achievement considered by the teacher *as regularly below the average, I: interviewer, 2L1: student 1, 2L2: student 2)*

Even among the high-achieving students, problems in understanding were evident. Only two high-achieving pairs applied the law of the conservation of mass correctly and without further prompts. One pair came to a correct explanation within their discussion. But one high-achieving pair of students did not come to the correct solution, because the students did not know whether conservation of mass was related to all initial substances and products, or only to those existing in a solid state. In their explanations, they stated that the mass of the products was bigger when considering that 'wood-oxide' was formed:

I: How heavy are the resulting products in comparison with the mass of the initial products?

1H1: Actually the result is heavier. One also has to weigh the resulting substance. Mostly oxygen adds to it and one usually counts the gas, too.

I: And when everything is taken into account?

1H1: Then it is heavier, because the oxygen adds to it.

(Learning group 1, students achievement considered by the teacher as regularly *above the average, I: interviewer, 1H1: student 1, 1H2: student 2)*

Problems were also evident when the concepts of volume, mass, and density were not well understood and sufficiently differentiated:

I: How heavy are the resulting products in comparison with the initial substances?

3L1: I believe it is less, it is less, definitely.

3L2: …and lighter.

3L1: …yes lighter.

3L2: There is already a gas at the end.

I: Imagine, you could catch all of the resulting products.

3L1: I believe, the volume is bigger afterwards, because yes… oh no, the oxygen is being consumed - I don't know.

3L2: Actually, it always stays the same during a chemical reaction.

3L1: But actually a chemical reaction changes the properties of matter.

3L2: …but when two substances.

3L1: No, if it is a closed system, the mass stays the same.

3L2: If one would catch everything and knows what one put in, then it is the same.

I: So, if you have a big room that could be weighed and you had the fireplace and the oxygen in the room. Then it stays the same, you think?

3L1: Well, the volume does. But the weight? I believe, air is not as heavy as a piece of wood. But, I don´t really know that.

(Learning group 3, students achievement considered by the teacher as regularly below the average, I: interviewer, 3L1: student 1, 3L2: student 2)

CONCLUSIONS AND IMPLICATIONS

Some main conclusions can de drawn from the results of the present study. Initially, it is important for us to understand that, in some cases, students provided superficial explanations that seemed to be correct, although they did not really understand the concepts that were involved in their explanations (Gabel & Sherwood, 1983; Lythcott, 1990). But, even low-achieving students were able to deal with explanations on the particulate level when discussing physical changes. In this study, it was evidently clear for all the students that chemical reactions are processes leading to completely new substances which have quite different properties from those of the initial substances. At the same time, they totally excluded the idea that chemical reactions could only result in changes in appearance or be mixtures of the initial substances. For the high-achieving students, the idea of a change into completely new substances was related to a change in the discrete particles that form totally new particles. The low-achieving students were partially able to correctly make this connection, indicating that they needed more scaffolding in constructing the correct relationship between the particle level and the macroscopic level.

Nevertheless, several common alternate ideas were prevalent, while students sometimes tended to overgeneralize the implications of their knowledge. Although the pupils studied and discussed (on the phenomenological as well as on the particle level) chemical changes where more than one substance was formed from one initial substance (carbonising sugar), chemical reactions were consistently, exclusively categorized as reactions starting with two initial substances and leading to one product. Students always considered chemical reactions to be exothermic, although they learned and differentiated between endothermic and exothermic reactions. Some students also continued to face difficulties in correctly differentiating chemical reactions from physical processes both at the phenomenological and the particle level.

The seemingly simple principle of the conservation of mass proved to be extremely difficult for students. The main issue was correctly identifying which substances to take into account. It was, however, encouraging to identify totally- (or nearly-) correct explanations at the particle level for both chemical and physical changes after one year of introductory chemistry lessons. From this perspective, the adopted approach seems to be more effective than other previously-implemented teaching approaches. Empirical data on learning the particle concept in authentic classroom situations does not exist for chemical education in Germany. The idea of introducing explanations of particulate matter in introductory chemistry courses is not unanimously accepted among the people responsible for textbooks and syllabi in Germany. Even if it were so, teaching methods and practices differ extensively.

All data and interpretations were discussed within the action research group. The practitioners in the group believed that it was beneficial to get feedback about their teaching. The teachers themselves felt that they were becoming more aware of the problems concerning matter and its properties. They felt that most of the problems were closely related to recognizing and explaining chemical change. Although this has been described in research literature (e.g., Krnel et al, 1998) and was extensively discussed with teachers, most of them did not take this aspect into serious account, and it was not connected to their own teaching experiences. Thus, after receiving feedback about their own practice from the interviews, they recognized the need to change their teaching. They more thoroughly wanted to include discussions about the concept of matter and about relevant properties of matter (not of objects) in their teaching. The teachers intended to develop guidelines with their students for dealing with chemical properties. These guides should allow the distinction between 'things' from the category of matter and 'things' from the category of 'not matter.' They should provide help in selecting the properties which are good for recognizing chemical reactions from those that are not good, respectively, and should to be taken into careful consideration (Leerhoff et al., 2002a, 2002b).

Also, the principle of conservation of mass was considered to be a major problem. Although all teachers mentioned that they had discussed the principle of the conservation of mass, they reflected that they had not recognized the importance of this principle for students' understanding of chemical reactions. The group now decided to more thoroughly include discussions and experimental work in their future teaching about the principle of the conservation of mass. They decided to put experiments into their teaching repertoire where iron wool or carbon is combusted with oxygen in a closed glass flask. This was recognized as potentially better for an understanding of the principle of conservation of mass and also for illustrating the role of gaseous compounds in chemical reactions. A more detailed discussion about particle explanation and its relation to the principle of conservation of mass was also considered to be really helpful. This seems to be related to the idea that the discrete particles themselves are not conserved but instead their building units, the atoms, are. A sufficient development of the concept of density also seems to be a prerequisite for recognising and characterising chemical changes more effectively.

Most of the described results have already been published, but the current results do not stem from the 'ivory tower' of research, but instead from authentic classroom situations. Thus, these results, despite their limited scope and generalizability, may have a stronger influence on teachers and their teaching strategies. In reality, the teachers themselves commented that they became more sensitive to their students' difficulties and expectations. There is hope that these experiences made the participants more sensitive towards the need to constantly evaluate the effectiveness of their teaching. This conclusion corroborates similar results reported by Valanides et al. (2003).

These experiences suggest that involving teachers in small scale empirical research can improve their sensitivity to teaching and learning and also promote their professional skills in assessment of and reflection on their own teaching (Eilks, 2003b). Obviously, extensive application of similar studies can foster mutual trust between teachers and researchers and can help overcome misunderstandings and prejudices existing between the practitioners and the research community in education (Huberman, 1993; Altrichter & Gstettner, 1993).

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