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STUDENTS' CORPUSCULAR CONCEPTIONS IN THE CONTEXT OF CHEMICAL EQUILIBRIUM AND CHEMICAL KINETICS

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ABSTRACT: This article consists of a review of a research program in chemical education in The Netherlands which aimed to develop students' ideas of macroscopic chemical phenomena together with their views of the particulate nature of matter. Starting from the initial and often naive corpuscular conceptions of the students, an attempt was made to develop these conceptions by letting students perform chemical experiments, and inviting them to explain their observations in corpuscular terms. In this program, students in the first year of chemical education (aged 14-15 years) were introduced to the concepts of 'chemical substance' and 'chemical reaction'. In the second year of chemical education, the program focused on the introduction of the concepts of 'chemical equilibrium' and 'chemical kinetics'. The results of the empirical investigation of students' conceptions and reasoning revealed that students of this age have limited abilities to reason in corpuscular terms. However, it was concluded that students can gradually learn to become more proficient in using corpuscular models as explanatory tools. This was indicated by a range of evidence, including that of students who used a simple model of colliding and moving particles to explain chemical phenomena in the areas of chemical equilibrium and chemical kinetics. [*Chem. Educ. Res. Pract. Eur.*: 2002, 3, 201-213]

KEYWORDS: *learning; student conceptions; particulate nature of matter; chemical reaction; chemical equilibrium; chemical kinetics*

INTRODUCTION

This contribution to the theme issue on structural concepts reports about a research program which was conducted in The Netherlands. In this country, chemistry is taught as a separate subject in secondary schools, starting in Grade 9 when students are about 14-15 years old. This program started with the work of Wobbe De Vos, who, while working as a chemistry teacher in secondary school, developed a specific educational approach for the introduction of fundamental chemical ideas to secondary school children in Grade 9. In this approach, an attempt was made to combine the introduction of the concept 'chemical reaction' as a macroscopic phenomenon, with the introduction of corpuscular ideas, to explain this phenomenon. Below, some features of this approach will be discussed in more detail, including some of the research findings of De Vos (see also De Vos & Verdonk, 1985a, 1985b, 1986, 1987a, 1987b, 1996).

In a later phase of the research program I conducted a study on the development of students' ideas and reasoning in the context of the introduction of the concept 'chemical equilibrium' and some basic kinetic ideas. This project built on the previous work of De Vos.

That is, an educational approach was designed for secondary school students in Grade 10 (age 15-16 years) which aimed to challenge students' initial ideas about 'chemical reaction', as well as their existing conceptions about corpuscular concepts. The development of students' ideas and reasoning about both the macroscopic phenomena and their corpuscular explanations was investigated. This article contains a review of the most important findings from this research project (see also Van Driel, De Vos, Verloop, and Dekkers, 1998; Van Driel, De Vos, Verloop, 1998).

THE PARTICULATE NATURE OF MATTER IN SCIENCE EDUCATION

In the research literature, there has been much attention for the ideas students have about atoms and molecules (e.g., Harrison & Treagust, 1996, in press; Johnson, 1998, Novick & Nussbaum, 1978; Lee et al., 1993). The ideas students have about the particulate nature of matter or often classified as misconceptions, naive conceptions, or alternative frameworks. De Vos and Verdonk (1996) have argued that in this literature, the corresponding scientifically accepted ideas about the particulate nature of matter are usually not explicitly discussed. Rather, they are referred to in brief, general terms (e.g., "the scientific conception", Lee et al., 1993). In an attempt to clarify what is considered a 'correct' conception of the particulate nature of matter in the context of introductory science education in lower secondary school, they reviewed the research literature and consulted the authors of several articles in this domain. This resulted in a list of eight points which, taken together, appeared to represent "a reasonably valid description of particles in elementary science education" (De Vos & Verdonk, 1996, p. 659), This list is summarised as follows:

1. All matter consists of entities called particles. Individual particles are too small to be seen. They behave as hard, solid, perfectly elastic and (except in chemical reactions) immutable objects.
2. Motion is a permanent feature of all particles, which, in gases and liquids, leads to frequent collisions of particles. There is a direct relation between the temperature of an amount of matter and the average kinetic energy of its particles.
3. In a gas, particles are evenly distributed over space, the empty space between the particles being much larger than the space occupied by the particles themselves.
4. Particles mutually attract each other, but the magnitude of the attraction decreases rapidly with distance.
5. In liquids and solids, the particles are much closer than they are in gases. Thus, their mutual attraction is much larger. Consequently, in solids the particles are only able to vibrate around a fixed position, whereas in liquids the particles may move from one place to another.
6. Different substances consist of different particles. All particles of one substance are mutually identical. A mixture of substances contains particles of two or more different species.
7. In the context of a chemical reaction, it is necessary to make a distinction between 'molecules' and 'atoms'. A chemical reaction is conceived as a rearrangement of atoms; the atoms themselves are conserved, whereas molecules of a certain species are transformed into molecules of different species.
8. There are about 100 different species of atoms. Each atom consists of a nucleus with a positive electric charge, surrounded by a number of negatively charged electrons. Chemical bond formation can be described in terms of the mobility of these electrons.

In educational research, some aspects of the particulate nature of matter have received much attention, for instance, the behaviour of molecules in gases (see e.g., Driver, 1985; Novick & Nussbaum, 1978). Other aspects, such as the idea that particles belonging to the

same substance are identical have been investigated less frequently (see, however, De Vos & Verdonk, 1987a). In this paper, the emphasis is on moving and colliding particles (point 2.), the identical nature of particles of the same species (point 6.), and the rearrangement of atoms during chemical reactions (point 7.)

INTRODUCING STUDENTS TO THE PARTICULATE NATURE OF MATTER IN RELATION TO THE CONCEPTS 'CHEMICAL SUBSTANCE' AND 'CHEMICAL REACTION'

In the language of chemists, corpuscular notions play a very dominant role. For instance, common substances such as 'salt' and 'acetone' are associated by chemists with the spatial arrangement of Na^+ and Cl^- ions, and the structural formula CH_3COCH_3 , respectively. On the other hand, young children will rather associate these substances with their taste, or smell. It is the chemist's knowledge of the particulate world that contributes much to the communication gap between chemists and non-chemists. Among others, this gap often results in problems in introductory chemistry courses in lower secondary school.

One way to solve this problem would be to teach molecules and atoms at a very early stage in such courses, trying to familiarise students with these ideas, so that they may become proficient in using these ideas in the same way as chemists do. This approach is most commonly adopted in introductory chemistry courses in lower secondary school, but not always to everyone's satisfaction. In fact, many of the learning problems and misconceptions reported in the literature may be seen as evidence of the failure of this approach. De Vos and Verdonk (1987a) concluded that teaching corpuscular models as clarifying or explanatory tools to understand the macroscopic behaviour of substances, is usually experienced by young students as "just another burden on the brain ... somehow many students seem unable to go beyond the stage of rote learning with regard to corpuscular models." (De Vos & Verdonk, 1987a, p. 692). The authors suggest that this lack of ability is related to the cognitive development of the students of that particular age group (Piaget & Inhelder, 1974). Tsaparlis (1997) has demonstrated that various theoretical perspectives, that is, not only the Piagetian developmental perspective, but also the Ausubelian theory of meaningful learning and the information processing theory, may be used to explain young students' difficulties to learn corpuscular concepts.

On the basis of the above, one might prefer to completely reject the use of corpuscular notions in introductory chemistry courses in lower secondary school, and postpone these ideas to later stages of education. However, De Vos opted for an alternative, that is, he tried to make use of the primitive and naive ideas young students already have developed about the particulate nature of matter at the moment when chemical education starts. After investigating these primitive and unscientific ideas, he developed a teaching approach which aimed to develop these ideas into scientifically more acceptable models, while introducing students at the same time to the (macroscopic) concepts of 'chemical substance' and 'chemical reaction'.

As a first step in this approach, the term *molecular species* was introduced as the corpuscular counterpart of the concept of 'chemical substance', as follows: 'All molecules of one substance belong to the same species, while molecules of different substances belong to different species.' This definition appeared to deviate substantially from the views held by the students. Although most of them accepted that, for instance, in the case of a sugar solution this would consist of sugar and water molecules, rather than 'solution molecules',

many problems occurred with respect to chemical reactions. For example, many students, after observing the burning of magnesium, would talk about the reaction product in terms of 'magnesium molecules in a burnt state'. A thorough analysis of such data revealed that most students attribute a particular identity to a molecule, and suppose the molecule keeps its identity throughout chemical reactions. Students would often reason in anthropomorphic terms in this respect, comparing molecules to people who grow old, but still remain the same persons (De Vos & Verdonk, 1987a).

To solve this problem, the word *identical* was introduced to the students, to refer to the idea that molecules of one substance are exactly alike in all respects, except for their position and motion in space. Using this idea, students should understand that if all magnesium molecules are assumed to be identical, the slightest change in any one of them, would turn it into a molecule of a different substance. Accordingly, the white powder obtained by burning magnesium, can not consist of magnesium molecules. This idea of objects being absolutely identical appeared to be problematic for students. Referring to objects in daily life (such as coins or apples), many students reasoned that objects are never completely identical. Obviously, this problem is related to the fact that the notion of 'identical molecules' is a theoretical concept which has no direct empirical basis. However, many students were able to use this notion to understand that molecules in hot and cold water belong to the same species, or to interpret phase transitions as results of changes in molecular motion. Most importantly, given the aims of the course, these students were able to understand that chemical reactions are processes which cannot be interpreted as resulting from changes in position or motion of molecules.

Reviewing the results of their investigations about this experimental approach to introducing corpuscular concepts, De Vos and Verdonk (1987a) concluded that their approach had specific strengths and limitations. The main strength concerned the fact that students, using the idea of linking a substance to a simple molecular species, were given a criterion with which they could interpret an observed change in terms of a chemical reaction. This idea had proved to be a useful tool for many students, helping them to make sense of their observations during chemical experiments. At the same time, however, students only understood the relationship between macroscopic properties of substances and molecular features at a very basic level. For instance, many students still believed that, since sulphur is yellow, each sulphur molecule must be yellow. In general, many students had problems accepting the hypothetical nature of the corpuscular world, which cannot be related directly to observations. However, such results were considered as unavoidable given the age of the students at this early stage of chemical education. On the whole, the authors concluded: "we believe we found a track that leads students from their primitive but authentic corpuscular ideas to at least a basic understanding of the substance and reaction concepts in chemistry" (De Vos & Verdonk, 1987a, p. 694).

In order to further investigate the potential of this "track", it was decided to conduct a follow-up project. In this project, a course was designed for students (now aged 15-16 years) in their second year of chemical education (i.e., Grade 10 in secondary education in The Netherlands). This course focused on the concepts of chemical equilibrium and chemical kinetics, because the introduction of these concepts requires students to revise their initial concept of a chemical reaction, and their related corpuscular ideas.

DEVELOPING STUDENTS' CONCEPTIONS OF CHEMICAL REACTIONS AND MOLECULES THROUGH THE INTRODUCTION OF CHEMICAL EQUILIBRIUM AND CHEMICAL KINETICS

In introductory chemistry courses in lower secondary school, chemical reactions are always associated with observable phenomena (e.g., change of colour, heat effect, precipitation of a solid, evolution of a gas), and chemical reactions are always presented as proceeding to completion, and as taking place in one direction only. The introduction of chemical equilibrium at a later stage, however, demonstrates the reversibility of chemical reactions and the possibility that chemical reactions do not proceed to completion. Moreover, the dynamic nature of chemical equilibrium requires students to assume that two opposite chemical reactions are taking place, in spite of the fact that this cannot be deduced from observations. As a consequence, the introduction of chemical equilibrium requires students to revise their initial conception of chemical reactions. At the corpuscular level, the adoption of the dynamic equilibrium concept requires the extension of the identical nature of particles of the same species with *statistical notions*. In addition, the concept of time needs to be included in order to preserve the idea that particles of the same species are identical: At a specific moment, a particle of type X may be formed, while at the same time, another X particle is converted at another place, keeping the total number of X particles constant.

The research on teaching and learning of chemical equilibrium has been reviewed by Quílez-Pardo and Solaz-Portolés (1995) and Van Driel and Gräber (in press). There is evidence of students' failure to conceive the dynamic nature of chemical equilibrium (see, e.g., Wheeler and Kass, 1978). Instead, chemical equilibrium is often perceived as static, that is, 'nothing happens' in a system in a state of chemical equilibrium. These students may believe that a chemical reaction must be observable. Bergquist and Heikkinen (1990) suggest that these and other students' difficulties are related to the content of chemistry courses. As the concepts of reversible reactions and chemical equilibrium are usually not introduced before the second half of these courses, these concepts are at odds with students' well-established conceptions of chemical reactions.

The introduction of kinetic ideas about chemical reactions also presents challenges to students' initial conceptions. The notion of 'reaction rate' requires students to understand that it takes time for a chemical conversion to proceed, and that this time is influenced by factors such as the temperature of the system and the concentrations of the reacting substances. A simple model of colliding particles may be useful to explain these observable influences in corpuscular terms.

Compared to chemical equilibrium, there have been remarkably few empirical studies in the domain of teaching and learning chemical kinetics. A review of this area is to be found in Justi (in press).

Educational design

Adopting a constructivist view of learning, our educational design applied specific conceptual change strategies (Posner et al., 1982). The course design (a) included assignments to challenge students' existing conceptions and (b) stimulated active student engagement through small-group discussions and hands-on experiments. These experiments were chosen not only to highlight aspects of the chemical content that are relevant from a cognitive perspective, but also to appeal to students from an affective point of view (e.g.,

fascinating colours and unexpected events), thus stimulating them to search for explanations (Chinn & Brewer, 1993; Pintrich et al., 1993). The students performed and discussed the experiments in small groups (3 to 4 students), guided by questions in the course material, in order to facilitate the process of explaining the observations. The entire course required 12 to 13 consecutive chemistry lessons of 50 minutes. Below, the features essential for the introduction of the equilibrium and kinetic concepts are described in more detail.

Reversibility; Chemical equilibrium

The course included chemical experiments which convincingly demonstrate the reversibility of chemical reactions as well as the possibility that a chemical conversion does not proceed to completion. For this purpose we chose the system of cobalt(II) tetrachloro and cobalt(II) hexahydrate complexes in iso-propanol (Spears & Spears, 1984). This system can be either pink, due to an abounding presence of the hydrate complex, or deep blue, indicating the presence of the chloro complex. The colour of the system is subject to the influence of both temperature (i.e., raising the temperature from 20°C to approximately 75°C results in a change from pink to blue, via a range of 'intermediate' colours, and vice versa), and additions (e.g., adding an amount of water to a blue solution results in the appearance of the pink colour). In the experimental course, students were presented with a test tube containing the pink solution. They were asked to heat and cool this solution by successive and repeated treatments in a warm and a cold water bath. Next, they were asked to heat a 'cold' pink solution to an intermediate temperature (55°C). In a final experiment, a 'cold' pink solution and a 'warm' deep blue solution were placed together in a water bath at 55°C. As a result, both solutions turned the same purple colour. After these experiments, students were asked to answer a series of questions, aimed at the explanation of these phenomena. The course also included other experiments with the same system, and with aqueous solutions of iron (III) thiocyanate complex (Sandell, 1959). These experiments, and the responses of the students, are described elsewhere (Van Driel, De Vos, Verloop, & Dekkers, 1998; Van Driel, De Vos, & Verloop, 1999).

Chemical kinetics

The course included a series of test tube experiments with aqueous solutions of potassium iodide and potassium peroxodisulphate ($K_2S_2O_8$). The students observed the appearance of iodine, resulting in a brown colour, under various conditions (i.e., temperatures ranging from 5°C to 60 °C; different initial concentrations of the peroxodisulphate solution). The experiments were concluded with a series of questions, inviting the students to explain their observations using their corpuscular ideas.

Research method

Research data were collected in regular Grade 10 chemistry classes in a dozen secondary schools in The Netherlands. The data included (a) the audio taped discussions of about twenty groups of students (age: 15 to 16 years) working with our course and (b) the written answers of some 40 to 50 groups of students to all the questions and assignments included in this course. The purpose of this research was to identify the types of reasoning students apply when chemical equilibrium and chemical kinetics are introduced to them in the manner

described above. Specifically, we aimed to explore which types of reasoning, both at the macroscopic and at the corpuscular level, would either promote or hinder the students' conceptual change process in this context. The research methodology incorporated the constant comparative method (Denzin, 1994) which involved the comparison of students' reasoning in discussions with their written answers, as well as researcher triangulation (Janesick, 1994) which aimed at agreement among individual researchers (i.e., Van Driel and De Vos) about the interpretation of students' reasoning in the data.

RESULTS

Reversibility; Chemical equilibrium

When studying the *reversibility* in the cobalt complexes system ('pink-and-blue'), students would usually be fascinated by the colour changes. Their observation that the colour of the system could be changed *repeatedly*, helped students to interpret their observations in terms of reversible chemical reactions. Their written responses to the questions related to these experiments indicated that the large majority of the students indeed interpreted the observed colour changes in these terms. A typical line of reasoning was:

'You can regain the blue substance again and again.'

At the same time, however, the results of these experiments appeared to surprise many students. This is illustrated by a fragment of a discussion in a group of students, who were watching the pink solution warming up in a water bath at 55°C:

- | | | |
|----|------|---|
| 1 | John | It's getting a little purple. |
| 2 | Ann | But it's going very slowly. |
| 3 | John | No, it's not going slower, it's only going to a certain point. |
| 4 | Ann | Yes, that's what I think as well. |
| 5 | Lisa | Yes, to the point of fifty-five degrees. |
| 6 | Mike | No, I don't think so. If you keep the tube at fifty-five, the reaction goes slower, but eventually it will be completely blue again. |
| 7 | John | No, I don't agree. |
| 8 | Ann | No. |
| 9 | Mike | Why will some molecules of the substance be converted and others not? That doesn't make sense! They're all the same substance, so they all have the same properties. So they will all be converted. It only will go slower. |
| 10 | Lisa | Hmm, yes, that makes sense. |
| 11 | John | Yes it does. |

It is important to note that from their observations in this experiment the students could not decide whether the colour was 'absolutely constant' or 'changing very slowly.' Therefore, John expressed an expectation (in 1), without supplying an underlying argument. On the other hand, Mike (in 9) argued from a corpuscular perspective. He applied the idea that molecules of the same species are identical in order to preserve his conception that eventually this chemical conversion will have to proceed to completion. In other groups, students discussing this experiment also reasoned that eventually the solution would turn completely blue. A typical macroscopic argument was:

‘Why would this reaction *not* continue until the pink substance is completely converted?’

The final experiment, during which a ‘cold’ pink solution and a ‘warm’ deep blue solution were placed together in a water bath at 55°C, convinced practically all the students that in the purple solution at a constant, intermediate temperature, the chemical conversion did not proceed to completion. Nevertheless, many students, although accepting this conclusion as an empirical fact, appeared to be confused or surprised by this incomplete conversion.

From their answers to the questions following the latter experiments, it appeared that the vast majority of the students believed that both the forward and the backward reaction actually do take place in the solution at 55°C. Accepting this view, they would immediately conclude that these reactions would have to occur with equal rates, because:

‘Otherwise, the colour would have to change.’

Thus, students were ready to accept the dynamic conception of chemical equilibrium. In most instances, the students’ line of reasoning proved to revolve around the idea that all conditions for both reactions to take place are satisfied. A typical written answer was:

‘Yes, when all substances are present together, they will always react.’

When they were asked for an explanation of this phenomenon in corpuscular terms, students usually ended up with notions of moving and colliding particles:

‘The molecules still move, so they can still touch each other.’

Specifically, some students would incorporate statistical notions in their explanation, for instance:

‘I think all molecules react, but also new molecules are being created all the time ... it’s not that the same molecules remain intact, but they are recreated.’

Or:

‘You shouldn’t think of a substance as one thing, but as billions of particles, and some of these particles unite, while other particles split up again.’

When discussing the consequences of the dynamic view, many students still demonstrated a tendency to connect the occurrence of chemical reactions with the colour changes they had observed earlier. Specifically, many students appeared to separate the two opposite reactions in either space or time. Bergquist and Heikkinen (1990) have reported a similar finding. It turned out from the discussions of students with each other and with their teachers that in such cases students could be helped by distinguishing between the ‘outside’ and the ‘inside’ of the equilibrium system. The former represents the macroscopic properties of the system, whereas the latter relates to the unobservable processes occurring within the system. Or, in the words of one student:

‘So the colour stays the same, but there is a whole lot of wild events going on inside.’

Obviously, the ‘inside’ of the system was often, but not always, described in corpuscular terms.

Chemical kinetics

We studied the students' responses to the experiments with potassium iodide and potassium peroxodisulphate, and the questions connected with these experiments. To explain the effect of changing concentrations of peroxodisulphate on the rate of iodine formation, students most commonly reasoned that 'less particles (per unit of volume) would lead to less collisions (per unit of time)'. Other students would emphasise that in a dilute solution, on the average, particles are at larger distances of each other, or, alternatively, there are more molecules of the solvent which 'are in the way'.

To explain the increase of reaction rate at higher temperatures, most students connected the notion of 'faster moving particles' with 'more collisions', or 'a higher chance of collisions'. In the latter case, again, statistical notions were incorporated in the students' reasoning. However, another group of students reasoned that when fast moving particles collide with each other, it is very likely that these particles will 'bounce back', without a change or reaction occurring. Some students added that the molecules 'would not have enough time to exchange atoms'. This conception is at odds with the view advocated by most chemistry textbooks for secondary education, in which it is argued that, to account for higher reaction rates at higher temperatures, collisions involving fast moving particles are more 'effective'.

DISCUSSION AND CONCLUSIONS

The overall aim of the research program discussed in this paper was to develop secondary students' ideas of macroscopic chemical phenomena together with their views of the particulate nature of matter. Specifically, the aim was to start from the initial and often naive corpuscular conceptions of the students, and develop these conceptions by letting them perform chemical experiments, and inviting them to explain their observations in corpuscular terms. In our program, students in the first year of chemical education (Grade 9; age: 14-15 years) were introduced to the concepts of 'chemical substance' and 'chemical reaction'. As a follow-up, in the second year of chemical education (Grade 10), the concepts of 'chemical equilibrium' and 'chemical kinetics' were chosen as the focus of study.

Chemical equilibrium

As for the introduction of the concept of 'chemical equilibrium', it was concluded that the notions of 'reversibility' and 'incomplete conversion' of chemical reactions can be successfully introduced as macroscopic phenomena, by letting students perform experiments which convincingly demonstrate these features of chemical reactions. These phenomena, however, are at odds with the way the nature of particles has been taught previously, in particular, with the idea that particles of the same species are considered identical and that they do not differ from each other in any way, except position and motion (De Vos & Verdonk, 1987a). From this conception of 'identical particles', students cannot explain why, in the case of reversibility or incomplete conversion, some particles of the same species seem to behave differently from other particles of the same species. Thus, students' corpuscular conceptions are challenged by asking them to explain these phenomena in corpuscular terms.

To solve this anomaly, the notion of 'dynamic equilibrium' may be offered as an explanatory model. In order to adopt this conception, students must accept the possibility that

a chemical reaction may occur although this is not indicated by changes at the macroscopic level. They then need to subscribe to the idea that two opposite reactions are taking place *simultaneously*. This idea appeared to present many students with either linguistic or conceptual difficulties. As a result, many students reasoned in terms of *oscillating reactions*, that is, they separated the opposite reactions in time or space. Nevertheless, many of the students eventually accepted the dynamic conception because it offered them the possibility to answer the questions and to resolve the confusion raised by both the reversibility and the incomplete conversion in the chemical experiments they had performed. The idea that the two opposite reactions proceed at equal rates appeared easy to accept, once students realised that this is a necessary requirement to explain the absence of macroscopic changes.

At the corpuscular level, the adoption of the dynamic equilibrium concept requires the extension of the identical nature of particles of the same species. In particular, the concept of time and statistical notions need to be included in order to preserve the idea that particles of the same species are identical. Many students appeared to struggle with this type of reasoning. Interestingly, we observed parallels between the reasoning of students and the reasoning of 19th-century scientists, who studied the incompleteness and the reversibility of chemical reactions. These phenomena were, at that time, incompatible with the molecular-kinetic theory of Clausius (see Appendix). In our studies, we found that, by reasoning in terms of moving and colliding particles, the students' reasoning often included notions resembling the 19th-century molecular-kinetic theory. In most cases, however, students' explanations remained incomplete or naive. The few students capable of giving adequate explanations in corpuscular terms implemented statistical notions in their explanations (see examples cited above), analogous to 19th-century explanations. A more detailed discussion of these parallels of students' reasoning with the history of chemistry can be found in Van Driel, De Vos and Verloop (1998).

Chemical kinetics

In our course, the introduction of chemical kinetics focused on a basic understanding of the concept of 'reaction rate', at both a macroscopic and a corpuscular level. For the majority of the students, this introduction did not cause conceptual problems. In particular, most students were able to use a simple model of moving and colliding particles to explain the effect of concentration on reaction rate. However, when asked to explain the effect of temperature on reaction rate, many students using this model, arrived at the wrong conclusion: they reasoned that collisions of fast moving particles would be less effective, because the particles would 'bounce back'. This problem is due to the limitations of the simple model of colliding particles which lacks notions of activation energy and spatial structures and orientations of the particles. A more advanced model, based on transition state theory, would incorporate the breaking and formation of bonds within and between the molecules. In our experimental course, however, such a model was not included, because we expected this to be too complicated for the students at this level.

Concluding this paper, the study of the development of students' corpuscular conceptions in the context of chemical equilibrium and chemical kinetics seems to support the belief expressed by De Vos and Verdonk (1987a) that our approach has the potential of guiding students from initially primitive corpuscular views towards scientific more acceptable views. Although we are aware of the limitations of young students' abilities to

reason in corpuscular terms, which requires them to argue from a hypothesis which is not based on empirical observations, we have become convinced that these students can gradually learn to become more proficient in using corpuscular models as explanatory tools. Although their explanations at this level often contain deficiencies from a scientific perspective, we prefer this approach in chemistry courses in secondary school to an approach which merely leads to rote learning of 'correct' corpuscular explanations.

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APPENDIX: HISTORICAL DEVELOPMENT OF CHEMICAL EQUILIBRIUM

In an article published in the middle of the last century, A.W. Williamson wrote about the 'dynamics of chemistry.' His starting point was the assumption that, in a pure substance, the atoms are being permanently exchanged between the different molecules in that substance. In order to explain why some chemical reactions do not proceed to completion, he assumed that in those cases products are being formed continuously. To account for the macroscopic fact that the quantities of the products involved do not change in time, he also assumed that the conversion of products to the original reactants keeps taking place as well. In the course of these two processes, the absolute number of atoms being exchanged per unit of time were supposed to be equal. In this respect, Williamson underscored the fact that the reactions concerned were reversible (Williamson, 1851-54).

A few years later, the physicist Rudolf Clausius published an explanation for the partial evaporation of liquids. In his molecular-kinetic theory, it was hypothesised that individual molecules of the same species can have different velocities at the same temperature. According to Clausius, the macroscopic phenomenon of evaporation of a liquid can lead to a state of equilibrium, which is not a state of rest in which evaporation no longer takes place. Instead, in such a state, evaporation and condensation take place at 'equal strength', therefore compensating each other. In microscopic terms, the number of molecules passing into the vapour phase on the average equals the number of molecules passing into the liquid phase (Clausius, 1857).

In the same period, it was discovered that within a certain range of temperatures, some gaseous chemical substances are only partially dissociated (e.g., ammonium chloride to ammonia and hydrogen chloride). The first scientist who correctly explained this phenomenon was the Austrian physicist Leopold Pfaundler. In an article published in 1867, Pfaundler put forward two possible explanations for the partial dissociation: *either* all molecules have undergone the same change (their cohesion has become looser and the distance between the atoms has increased), *or* a fraction of all molecules has completely dissociated, whereas the rest are completely bound. Pfaundler rejected the first explanation, as it didn't account for certain experimental facts (e.g., the presence of ammonia and hydrogen chloride had been determined in the vapour of ammonium chloride). The second explanation, on the other hand, was at odds with the idea that molecules of the same species were considered identical. From this point of view, Pfaundler argued: "It is hard to explain why, at the same temperature, one part of the apparently identical molecules would dissociate, while the rest of these molecules would remain unchanged." (Pfaundler, 1867, p.

57; translated from German by the author). Nevertheless, Pfaundler accepted this explanation by adopting Clausius' theory that identical molecules can be in a different state of motion. Pfaundler reasoned in terms of moving and colliding particles, whose kinetic energy is spread around a certain mean value, which is related to temperature. As a consequence, at any moment at constant temperature and pressure, some molecules may decompose while new ones are formed by collisions. In a state of equilibrium, the number of molecules decomposing within a certain period of time must equal the number of molecules being formed (Pfaundler, 1867).

From this historical study, it appears that the macroscopic phenomenon of incomplete chemical conversion was the object of several scientific studies during the 19th century. In trying to explain this phenomenon, scientists' reasoning was based on a microscopic (i.e., molecular-kinetic) theory. This theory had to be extended with statistical notions. That is, starting from the idea that individual molecules of the same species are in a different state of motion, scientists reasoned that such molecules, in spite of being identical, may be engaged in different processes (i.e., decomposing or uniting) at the same time.

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