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<td><strong>Author(s)</strong></td>
<td>Kam-Wah, Lucille, Lee</td>
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<td><strong>Source</strong></td>
<td>28th Annual Conference of the Australasian Science Education Research Association, Adelaide, Australia, 4 - 7 July 1997</td>
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CONCEPTUAL UNDERSTANDING AT THE MICROSCOPIC LEVEL*

Kam-Wah, Lucille, Lee
Nanyang Technological University

ABSTRACT

A growing area of interest in chemical education has been the research associated with conceptual understanding at the microscopic level. This study investigated the conceptions of 10 university chemistry lecturers, 85 pre-service chemistry teachers and 23 Grade 9 chemistry students about the particulate level of a chemical reaction, namely, the heating of copper (II) carbonate. Five characteristic conceptions were identified on the basis of their diagrammatic representations of particles. These were: (A) Formation of intermediate; (B) Formation of free atoms, ions, or radicals; (C) Combination of A and B: Formation of free atoms, ions, or radicals first, and then intermediate; (D) Direct combination of copper and oxygen atoms in the copper (II) carbonate lattice; and (E) Products directed. Both the lecturers and the teachers held an identical view about the reaction mechanism, namely that the decomposition of copper (II) carbonate goes through a transition stage by forming intermediate. In contrast, even though the students were familiar with this reaction, most of them held a naïve conception suggesting that copper and oxygen combine directly either as free atoms or as ions to form copper (II) oxide without going through the transition stage. Some students did not even have any notion of how the atoms in the copper (II) carbonate lattice interact or are rearranged in the reaction.

INTRODUCTION

Recent research has shown that teachers tend to teach chemistry far more at the symbolic level than at the macroscopic and microscopic levels (Johnstone, 1991). Students make little sense of chemistry partly because they are not shown the actual chemical phenomena (macro-level) and partly because the phenomena are not explained to them in terms of atoms and their kinetic properties (micro-level). The macro- and micro- levels have been emphasised as distinct and different perspectives for the same phenomena (Berkheimer et al., 1988; Ten Voorde, 1990); and both, but especially the micro-level, are considered important for conceptual understanding (Johnstone, 1991). A number of research studies show that students have difficulties in understanding chemistry concepts especially at the microscopic level (Yarroch, 1985; Nurrenbern & Pickering, 1987; Lythcott, 1990; Sawrey, 1990; Lee, Goh & Chia, 1993). Some examples of students' difficulties in this aspect were reported in an earlier paper (Lee, 1996). However, research studies also suggest that students' understanding of chemistry can be greatly facilitated if they are shown the microscopic representation of particles in a chemical

reaction (Gabel, 1993; Noh & Scharmann, 1997). Noh and Scharmann (1997) investigated the instructional influence of a molecular-level pictorial presentation of matter on Korean students’ conceptions and problem-solving ability. For the treatment group, 31 pictorial materials were used teaching 21 hours of Korean academic high school chemistry classes. For the control group, traditional instruction was used instead. It was found that the instruction with pictorial materials at the molecular level helped students acquire the correct conception more scientifically, although it had no facilitating effect on their problem-solving ability.

In the light of the above research findings, it is believed that conceptual understanding can be further improved if teachers incorporate the use of the particle model (showing the interaction between atoms and molecules at the microscopic level) in their chemistry instruction. But are chemistry teachers confident enough to use the particle model? What are their particulate perceptions of some chemical changes commonly taught in schools? A study of students’ microscopic conceptions of two common chemical reactions was undertaken by Laverty and McGarvey (1991). As an extension of their study, the researcher (Lee, 1996) studied teachers’ conceptions of a chemical reaction, namely, the burning of magnesium in air, in terms of the diagrammatic representation of particles. The purpose of the study was to find out how different teachers perceived chemical reaction on the same aspect. Two groups of teachers took part in the study; these comprised 85 pre-service chemistry teachers and 10 chemistry university lecturers. It was found that the two groups had different views about the reaction mechanism. The lecturers were in favour of the ‘intermediate’ approach, whereas the pre-service teachers preferred the ‘free particles’ approach. The ‘intermediate’ approach means that before magnesium oxide lattice is formed, magnesium lattice and oxygen molecules form intermediate in a transition state. The ‘free particles’ approach means that the magnesium lattice or oxygen molecules, or both of them, form free atoms, ions, or radicals, and then join together forming magnesium oxide lattice. It was also found that many pre-service teachers did not actively hold the correct science concept about the arrangement of particles in solid. In their diagrams, magnesium oxide lattice figured as loosely packed magnesium oxide molecules.

This paper is in continuation of the above-mentioned work (Lee, 1996), and reports on three groups of subjects: university chemistry lecturers, pre-service chemistry teachers, and Grade 9 chemistry students. Their differing conceptions of one single chemical reaction, in this case the heating of copper (II) carbonate in air, are investigated on the basis of their diagrammatic representation of particles. A new group, students, was added with a view to widen the scope of the study. As well as comparing the three groups’ responses at the microscopic level, the paper addresses itself to some implications of the study.

METHOD

Sample
The study involved 85 pre-service chemistry teachers who were enrolled in the one-year Postgraduate-Diploma-in-Education (PGDE) programme of the National Institute of Education, 10 chemistry lecturers from a local university, and 23 Grade 9 (aged 15)
chemistry students from an independent school in Singapore. The 85 pre-service chemistry teachers (will be called teachers from here onward) were made up of 3 cohorts who took chemistry teaching method course with the researcher in the academic years of 94/95, 95/96 and 96/97. Their break-up is: 94/95: 21; 95/96: 24; 96/97: 40. These 85 teachers were science graduates who did chemistry in their first degree study. The 23 students involved in this study were the high achievers among the top 10% of the national cohort. They took pure chemistry as one of the school subjects.

Procedure
Even though both the teachers and students were familiar with the reaction involved, the researcher demonstrated the experiment, the heating of copper (II) carbonate in air, to them separately. The carbon dioxide gas produced in the reaction was demonstrated by using limewater. The researcher also drew the attention of the teachers and students to the colour of the residue in the test-tube. It was black which indicated the presence of copper (II) oxide. After the reaction phenomenon had been shown, the individual students and the teachers in groups of 4-6 were asked to make a diagrammatic representation of the particles to show the reaction mechanism. The molecular diagram of copper (II) carbonate (Figure 1) was shown to them also. Since the lecturers were all familiar with the reaction, they were approached individually and invited to do likewise. They were all advised to use circles (O) or shaded circles (●) etc. to represent the different particles in their diagrams. The researcher interviewed the lecturers to seek clarification if the responses were ambiguous.

![Molecular Diagram](image)

Figure 1. The molecular diagram of copper (II) carbonate

RESULTS

The 50 resulting diagrams were examined for common characteristics in the particulate representations of the reaction mechanism. Five such characteristics were identified. They can be identified in conceptual terms as:

(A) Formation of intermediate;
(B) Formation of free atoms, ions, or radicals;
(C) Combination of A and B: Formation of free atoms, ions, or radicals first, and then intermediate;
(D) Direct combination of copper and oxygen atoms in the copper (II) carbonate lattice; and
(E) Products directed.

The first four conceptions, A, B, C and D, concern the way the particles of the reactant interact with each other before carbon dioxide and copper (II) oxide are formed. The
conception E does not show the interaction between atoms. The distribution frequency of the three groups of subjects holding the five conceptions is shown in Table 1.

**TABLE 1**

<table>
<thead>
<tr>
<th>Characteristic Conception</th>
<th>Lecturers (n=10)</th>
<th>Teachers (n=85, Groups=17)</th>
<th>Students (n=23)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>8</td>
<td>12</td>
<td>5</td>
</tr>
<tr>
<td>B</td>
<td>0</td>
<td>0</td>
<td>13</td>
</tr>
<tr>
<td>C</td>
<td>2</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>D</td>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>E</td>
<td>0</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>Total</td>
<td>10</td>
<td>17</td>
<td>23</td>
</tr>
</tbody>
</table>

(A) **Formation of intermediate**

Copper (II) carbonate is an ionic compound where copper and carbonate ions are attracted to each other through the transfer of electrons from copper to the carbonate radicals. The bonding between copper and carbonate ions in the lattice is electrostatic attraction (ionic bonding). The extra electrons in the carbonate ion are distributed among the three C-O bonds as shown in Figures 2a and 2b, the conjugate anion. Upon heating, the electrostatic attraction between Cu\(^{2+}\) ion, and the conjugate anion, CO\(_3\)^{2-}, is slowly getting weaker, while the attraction between Cu\(^{2+}\) ion and one of the oxygen ions from the anion is getting stronger (Figures 2b and 2c). At the same time, one of the C-O bonds in the conjugate anion, CO\(_3\)^{2-}, is also getting weaker (Figure 2c). Subsequently, these C-O bond and the Cu-conjugate anion bond are finally broken, while Cu\(^{2+}\) and O\(^{2-}\) join together and form copper (II) oxide. The two processes, bond breaking and bond formation, occur simultaneously in the transition stage. An alternate representation of this mechanism is shown in Figures 2d and 2e. As a result, the crystal lattice of copper (II) carbonate breaks down to give copper (II) oxide lattice and simultaneous liberation of carbon dioxide. Copper (II) oxide has electrostatic attraction between its constituent atoms, whereas carbon dioxide shares electrons between the atoms. To illustrate this point, 3 diagrams, one by a lecturer (L5), one by a group of teachers (T6), and the other by a student (S19), are shown in the Appendix, Examples 1, 2 and 3.

Majority of the lecturers (8 out of 10) and the teachers (12 out of 17 groups) shared the same conception of intermediate being formed at the transition stage of the reaction, but only a minority of students (5 out of 23) had this conception. The lecturers were more thorough as compared to the students in presenting the interaction mechanism of the reaction in diagrams.
Figure 2. Reaction mechanism of heating copper (II) carbonate and the intermediate.

(B) Formation of free atoms, ions, or radicals
Heat causes copper, carbon, and oxygen atoms in the copper (II) carbonate lattice to vibrate and finally break into free atoms, ions, or radicals. The free particles may be formed as shown in Figure 3. These particles, then, combine to form copper (II) oxide as shown in Figure 4.
Figure 3. Formation of free atoms, ions, and radicals

\[
\begin{array}{c}
\text{Cu}^{2+} + \text{O}_2^- & \rightarrow & \text{Cu}^{2+} + \text{O}_2^-
\end{array}
\]

copper ion + oxide ion \rightarrow copper (II) oxide

\[
\begin{array}{c}
\text{Cu} + \text{O} & \rightarrow & \text{Cu} + \text{O}
\end{array}
\]

copper atom + oxygen atom \rightarrow copper (II) oxide

Figure 4. Direct combination of free particles to form copper (II) oxide

Thirteen students had this conception. Two examples are shown in Appendix, Examples 4 and 5. In most cases, these students simply drew the particles which they could think of (Figure 3), so that eventually copper can combine with oxygen to form copper (II) oxide and carbon with oxygen to form carbon dioxide. In contrast, the lecturers and teachers did not see the formation of copper (II) oxide a direct combination of the free particles. Instead, they considered its formation through the formation of intermediate between these free particles.

(C) Combination of A and B: Formation of free atoms, ions, or radicals first, and then intermediate

Two lecturers and 4 groups of teachers shared a common conception, namely, the combination of Conception A and Conception B. Once the free particles, e.g. \(\text{Cu}^{2+}, \text{O}^2-, \text{CO}_3^{2-}\) ions, and \(\text{O}\) atoms, are dissociated from the copper (II) carbonate lattice or from the gaseous copper (II) carbonate on heating, they continue to form intermediate as shown in Figure 5. To illustrate this point, 2 examples are shown in Appendix, Examples 6 and 7. Of those sharing this conception, some showed the ionic bonding of copper (II) oxide by including ‘+’ and ‘-’ in their diagrams.

The two lecturers have slightly different views of where the free particles form in their diagrams. L8 considered the oxygen in the carbonate radicals upon heating broke into free atoms and then attracted to copper ions. The two processes, bond breaking and reforming occurred simultaneously in the lattice. However, L9 considered the copper (II) carbonate lattice upon heating turned into gaseous \(\text{Cu}^{2+}\) and \(\text{CO}_3^{2-}\) ions, the breaking and reforming of bonds then occurred simultaneously after that.
Figure 5. Formation of free particles and then intermediate before forming Copper (II) oxide

(D) **Direct combination of copper and oxygen atoms in the copper (II) carbonate lattice**
One group of teachers (T16) and 2 students thought that the copper and oxygen atoms in the copper (II) carbonate molecules combined directly due to the bond weakening between Cu and the conjugate anion, $\text{CO}_3^{2-}$, and between C and O bonds by the heat (Figure 6). How the copper and oxygen atoms actually interact with each other, after the bond breaking between Cu and conjugate anion, and between C and O was not shown in their diagrams. The diagrams of T16 and S2 are shown in Appendix, Examples 8 and 9.

Figure 6. Direct combination between copper and oxygen atoms in the lattice

(E) **Products directed**
Three students ignored the particulate representation of the reaction mechanism and straightaway showed the two products, copper (II) oxide and carbon dioxide (Figure 7).

Figure 7. Heating copper (II) carbonate forming copper (II) oxide and carbon dioxide
DISCUSSION AND IMPLICATIONS

In this study, all the lecturers and the majority of the teachers (16 out of 17 groups) share the same conceptions that the effect of heat on copper (II) carbonate causes the formation of intermediate (Conception A and Conception C), in which the bond breaking and reforming take place simultaneously. The breaking and reforming of bonds take place either in the copper (II) carbonate lattice (Figure 2) or between the atoms, ions, and/or radicals (Figure 5). For the students, only a minority (5 out of 23 students) show the same conception (Conception A) as the lecturers and teachers. Majority of the students (13 out of 23 students) consider that the lattice is firstly broken into free particles (Figure 3). These particles, e.g. Cu atoms/ions and O atoms/ions then simply join together (Figure 4). Some of the free particles shown by the students such as Cu and C atoms (Figure 3) are unrealistic from scientific point of view because upon school laboratory heating condition, the free atoms of the ionic compound lattice cannot be easily obtained. Their choice of free particles presented are likely to be a guess than a scientific deduction from their prior knowledge. Moreover, some students (5 out of 23) did not seem to know about breaking or forming of bonds in the reaction (Conception D and Conception E), even though they were told to draw particles to show the reaction mechanism.

From the above results, it is evident that the lecturers and teachers show a deeper understanding of the reaction mechanism in terms of the particulate model of matter. The lattice obtains heat energy that activates its constituent atoms or ions into forming intermediate in the transition stage where the atoms or ions undergo bond breaking and reforming. On the other hand, many students cannot draw a correct particulate diagram to explain the reaction in the microscopic system. They naively thought that all or parts of the constituent atoms of CuCO\(_3\) were broken upon heating then reorganised again to form the two observed products, CuO and CO\(_2\). Figure 8 illustrates this point. Their understanding of the reaction at the microscope level appeared to be absent. As this can be seen from their interpretations of the reaction mechanism which explicitly derive from the chemical equation, CuCO\(_3\) → CuO + CO\(_2\). The results of this study support the work done by Ben-Zvi, Silberstein and Mamlok (1990) that students do not understand the dynamic nature of the particulate interactions, they perceive compound as being formed by simply sticking fragments together or just add them up as long as they give rise to the products of the reaction.

\[
\begin{align*}
\text{CuCO}_3 & \rightarrow \text{CuO} + \text{CO}_2 \\
\text{Cu} + \text{C} + \text{O} + \text{O} + \text{O} & \\
\end{align*}
\]

Figure 8. An example of students' diagrammatic representation of the reaction mechanism

This study has shown that the scientists and teachers, but not the students, agree with each other in their conceptual understanding of the reaction mechanism of the
decomposition of copper (II) carbonate compound upon the effect of heat. The agreement between the scientists and teachers may be attributed to the chemistry course, organic chemistry they took in the university where the teachers learned carboxylic acids and its functional derivatives. The results, on the other hand, show that the students have little conceptual understanding of the reaction at the microscopic level and this reflects that they have not been exposed to the three levels of teaching.

In comparison with the earlier study (Lee, 1996), the scientists and teachers were asked to interpret the reaction mechanism of burning magnesium in air by drawing the particles involved. The results of the two studies are very different. A number of teachers from the earlier study had different conceptions from the scientists. The teachers perceived magnesium lattice and/or oxygen molecules upon heating turned into free particles before they combined and formed magnesium oxide, whereas the scientists believed that magnesium oxide was formed through the formation of intermediate between magnesium lattice and oxygen molecules. The particulate nature of the reaction of burning magnesium in air has not been reported in literature and no one seems to talk about it. The findings of these two studies confirm Gabel et al.'s (1996) findings that the teachers do not teach chemistry by integrating the three levels: macroscopic (physical phenomena), microscopic (particles) and the symbolic levels (chemical and mathematical). Teachers do not generally feel confident to teach chemistry at the microscopic level, because “they have never had this kind of instruction in their own chemistry courses or really considered it in their own thinking”. Moreover, the emphasis of chemistry curriculum and textbooks are predominately at the symbolic level. Teachers lack support in terms of teaching resources and references should they teach chemistry at the microscopic level. More research on ways of teaching students relate the three levels of representing matter to enhance conceptual understanding has significance for today’s students as well as those of the future.

REFERENCES


APPENDIX

Example 1 (L5)

Example 2 (T6)
Example 3 (S19)

Example 4 (S6)

Example 5 (S7)
Example 6 (L9)

Example 7 (T15)
Example 8 (T16)

\[
\text{Copper Carbamate} \quad \text{Cu}_2\text{CO}_3 \cdot \text{H}_2\text{O} \xrightarrow{\Delta} (\text{CO}_2^{\text{g}}) + (\text{CO}_2^{\text{aq}}) + \text{H}_2\text{O}(\text{l})
\]

Example 9 (S2)