Bond Energies and Models at Key Stage 4.

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Chair's Note: This paper is based on a study in an English school. Year 11 refers to 16 year old students for whom school is compulsory. Year 12 refers to optional classes for 17 year old students, and Year 13 is the pre-university year. In England, courses are much more specialised at this level than in the US and, consequently, fewer subjects are studied. Much of the A level work would be carried out in college in the US but the systems are not exactly comparable.

Introduction.

The National Curriculum for England and Wales (DFE, 1995) specifies three areas of energy transfer in chemical reactions that pupils should be taught as part of science attainment target 3 (Sc3), 'Materials and their Properties' at key stage 4 (14-16 year olds). These are that: changes of temperature often accompany reactions; reactions can be exothermic or endothermic; making and breaking chemical bonds in chemical reactions involves energy transfers. The Science National Curriculum for 2000 (DfEE, December 1999) includes an almost identical reference to the energy transfers involved in making and breaking chemical bonds.

Some problems with taught models.

From experience and conversations with both science teachers and Year 10 and 11 students, ideas about energy transfers during the making and breaking of chemical bonds frequently meet with difficulty. Four possible reasons for these are: pupils' difficulty with visualising the processes involved; pupils' numerical confidence and competence; teaching approaches to this topic, and the variety of textbook explanations.

Visualising molecules.

There may be problems with the abstract nature of the task; in particular a problem with the ability to transfer or visualise a concept from a molecular, sub-microscopic level, to a macroscopic level and, importantly, *vice versa.* Commenting on this problem, Boo (1998) notes that:

> Almost everything within chemistry is based on an understanding of the world of particles and their interaction, which cannot be experienced or felt, or easily deduced from macroscopic phenomenon. (Boo, 1998, p577)

The problem may go further than this. Not only may there be a problem with the visualisation of particles but with understanding particles themselves. Taber (1997) has demonstrated that even A level students may hold alternative conceptions about the nature of bonding.

Numerical skills.

Students may not be confident with the numerical skills needed to perform what many teachers may regard as the simple arithmetic needed for calculations. They may not have the conceptual skills or understanding of directed numbers; may have a degree of anxiety about using numbers, or may have difficulty transferring skills from mathematics to science (Lenton and Stevens, 1999).

Approaches to this topic.

With the emergence of balanced double award science at key stage 4, it may be that many schools do not find it easy to maintain the old system of every teacher teaching their specialist subject (Childs, 1998). This situation may be exacerbated by shortages of physical science specialists and a greater reliance on biological scientists in some areas. Furthermore, with an increasing trend towards mixed arts and sciences at A level, modular degree programmes and more mature entrants, there is no guarantee that new science teachers may be familiar with ideas about bond energies. With less familiar topics there is likely to be less confidence and a tendency to rely more on textbooks, either at the same level (GCSE) or using A level texts for preparation.

Textbook explanations.

A brief review of some textbook examples indicates that the topic of bond energies is treated in a way that may cause confusion by *assuming* a grasp of the terminology, familiarity with the models depicted, confidence with the numbers used and understanding at the sub-microscopic level - often all at the same time.

In older textbooks (which may still be used for reference purposes) there may often be little more than a brief mention of the meanings of the terms 'exothermic' and 'endothermic' (eg. Hart, 1978). Some older texts may go further with energy level diagrams and arithmetical ideas about exothermic (negative) and endothermic (positive) reactions (eg. Clynes *et al* 1971; McDuell, 1979) and McDuell (1979) does provide a brief explanation of energy changes during bond formation and breaking. These approaches assume that:

- the reactions presented are familiar to students;
- students appreciate the idea that positive is an upward movement and negative is downward;
- the numbers attached to the changes have meaning.

Do we assume too much?

The next group of textbook examples covers GCSE Chemistry *prior* to the introduction of the National Curriculum in 1989. The first of these (Hill, 1986) again provides explanations and examples for the meanings of 'exothermic' and 'endothermic', but this time a pictorial model is used to show heat losses and gains to the surroundings. The example of the neutralisation reaction of hydrochloric acid and sodium hydroxide to form sodium chloride and water is used. An energy level diagram is shown and the symbols used, such as ΔH, the arrows and the numbers are explained. However, there is little explanation about what is happening with the bonds other than: 'Chemical energy in the hydrochloric acid and sodium hydroxide is partly changed to chemical energy in the sodium chloride and water and partly lost as heat' (p190). This explanation almost undoes the clarity of the previous models and descriptions by its lack of detail at the particle level [I have deliberately used the term 'particle level' to avoid confusing the explanation about what occurs with ions, molecules and bonding which would be rather complex with this example]. The second of these examples (Hunt and Sykes, 1984) uses pictorial space-filling models for the formation of water from hydrogen and oxygen which are drawn on to an energy level diagram; the assumption being that students are familiar with these models. It mentions the making and breaking of bonds and the differences between the energy given out and the energy needed. It appears to deliberately avoid using actual figures but then directly introduces a numerical question. Although this model combines a number of useful features, it is almost trying to do too much within a short space.

The third group of examples is from textbooks written in response to National Curriculum requirements and therefore overtly covers the topic of bond energies. The first of these (Ryan, 1996) provides clear explanations about bond breaking and making, gives pictorial ball-and-stick style models of the molecules of hydrogen, chlorine and hydrogen chloride on an energy level diagram and tries to relate this to the *magnitude* of the changes. The section on calculating the ΔH for the reaction is clearly set out. The problems with this approach are, again, that there is an assumption of familiarity with the phenomenon and models and it attempts to cover too much ground in such a small space. The second of these (Ramsden, 1994) is more complex in both the examples used, and possibly confusing in the method of depicting them; it is not very clear from the diagrams which bonds are broken or formed or the magnitude of the energy changes involved.

From this brief review of the textbook explanations it appears that this difficult area of chemistry education needs to be taken in carefully sequenced stages using models that provide clarity rather than confusion. Indeed, this whole area may be a subject for further review.

A possible model.

Outline.

This model was deliberately constructed with this particular order. Firstly, an example of the phenomenon is presented. Secondly, a qualitative explanation is presented and discussed. Thirdly, the discussion leads to a quantitative explanation.

Practical aspects

The phenomenon is the burning of hydrogen in the oxygen in air where the hydrogen is prepared by the reaction of a small piece of magnesium with approximately 5cm^3 of hydrochloric acid in a small test tube. The hydrogen combines with the oxygen in the air to form water:

$$2H_2 + O_2 \dashrightarrow 2H_2O$$

If the hydrogen gas is tested with a lit spill a tiny explosion will be observed with a small flame and a distinctive 'squeaky pop' sound.

[*Safety note*: 2 mol dm^{-3} hydrochloric acid is irritant, higher concentrations are corrosive. Small test tubes (10 cm^3) should be used, as there is less risk from explosion; safety goggles should be worn]

A qualitative model involves pupils making three-dimensional ball and stick models of hydrogen, oxygen and water molecules. If they are only given a 'ration' of four hydrogen and two oxygen 'atoms', they should soon realise which bonds need to be broken and formed to produce water.

For the quantitative model the three-dimensional models of the hydrogen, oxygen and water molecules are provided again but the bonds are labelled with pegs with the numerical bond energies written on them. It should be possible for pupils to see the amount of energy required for breaking and making these bonds. If the pegs are placed in one container as the bonds are broken and another container when they are formed it should be possible to account for the net difference as being the energy produced by the exothermic reaction.

[bond energies: H-H: 436; O=O: 498; O-H: 464. All kJ mol^{-1}]

At the same time these values from the two containers can be mapped on to graph paper to produce an energy profile of the kind found in textbooks

Why this approach?

This particular phenomenon, the burning of hydrogen, is selected here because it is easily demonstrated or carried-out by students in the laboratory, has historical significance (the 'Hindenburg' airship) and requires simple apparatus that is available in most schools. The 'Molymod' models may be substituted with other three dimensional models as needed. Importantly, this example is a good visual and audible one to start with as:

> Pupils tend to identify a chemical reaction by unusual or unexpected happenings: fizz, explosion or change of colour. (Driver *et al*, 1994, p86)

A qualitative approach is adopted as a second step as it attempts to model, on a large scale, the phenomenon and avoids any problems with the mathematics at this early stage.

A quantitative model builds on the qualitative model when it is fully understood 'what is going on' in terms of bond breaking and bond making; this is aided by labelling the bonds.

Some results from empirical studies.

Two groups were studied. The first study was very preliminary, using an upper- middle ability Year 11 class of thirty students where the model was used as part of a normal teaching sequence. The second, more detailed, was with a group of eight Year 12 students just starting an A level Chemistry course. In both cases the model was presented and the students' responses noted. With the second group, particular questions were asked about this model.

With the first, preliminary, Year 11 group a number of aspects were noted:

- Ideas about exothermic and endothermic changes were understood (from previous experience of practical work with displacement reactions and neutralisation);
- The use of three-dimensional models was unfamiliar to most students; they lacked confidence with re-arranging the models (balls) of atoms, with using the springs to represent bonds and did not easily make a connection between the bond energies and bonds;
- A number of students expressed more confidence with a view of two-dimensional, board based, structures of molecules and the bond energies associated with them.

With the second, Year 12 group, there was an apparent difference in the level of understanding, both with their appreciation of the phenomenon and with their responses to the model:

- They showed a preference of starting with the chemical equation, in order to work out the number of moles of reactants and product involved;
- Two students showed a preference for starting with a two-dimensional model of hydrogen, oxygen and water. They were then able to transfer the two-dimensional models to three-dimensional 'ball-and-spring' models with ease;
- They readily appreciated that bond breaking involved an 'energy input' and that bond making involved an 'energy output';
- They were able to manipulate the (directed) numbers in order to obtain a net energy change for the reaction;
- They appreciated that this net energy change resulted in the explosion of hydrogen.

When questioned, all the students in the group admitted that this exercise would have been difficult had they been given the bond energy data alone and that the use of models had been a definite help. They were, however, divided about the *type* of model. Of the three who expressed a preference, two agreed that the three-dimensional models were better but one considered the two-dimensional model to be preferable. Whichever model was used, all the students in the group considered it necessary to have the different atoms marked clearly; they thought that the colours were important.

Some conclusions and discussion.

Firstly, the level of understanding between the Year 11 and the Year 12 groups was very different. This cannot be solely due to ability level as the two groups were not that different. There must be other factors involved here and I would suggest that *motivation* and *confidence* within the groups are important. Secondly, there was a lack of familiarity with the use of three-dimensional models and the Year 11 students in particular fell back on the more comfortable use of two-dimensional board models. Thirdly, there was uncertainty by the Year 11 students with the numerical calculations involved. This almost suggests that this topic should be taught at a later stage than Year 11? If this topic is taught at GCSE in Year 11, there are implications for the use of these types of models for teaching. It appears that both two *and* three-dimensional models should be presented, that the atoms are clearly marked or coloured and that science teachers should provide positive encouragement for the numerical skills needed (Lenton and Stevens, 1999).

One obvious limitation of this empirical study must be that of sample size. However, these are only preliminary results where the topic arose as part of a normal teaching sequence and these first steps have been taken to extend it as an ongoing project. The intention is to follow-up and continue this apparently difficult area of chemistry education in the future, using taped interviews following exercises with a number of small groups containing two or three students.

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