VICTORIAN CURRICULUM AND ASSESSMENT AUTHORITY

VCE Chemistry Units 1 and 2: 2007–2014

Introduction

Huge advances have been made in the application of the fundamental principles of chemistry over the last 10–15 years leading to the emergence of new areas. These areas include nanotechnology, green chemistry and biotechnology.

Contemporary studies in chemistry require students to develop an understanding of how the study of particles (nature and behaviour) at the 'nano' level has led to the development of new materials with specially designed properties and newer or different uses for older materials.

Students should also be encouraged to consider the future possibilities of research, breakthroughs, and any associated community, social or ethical issues related to the emerging areas of chemistry.

To assist teachers to implement the *VCE Chemistry Study Design Units 1 and 2:* 2007–2014, the following expert paper has been prepared to provide up-to-date information and explanation of important terms and concepts, and is of particular relevance to Unit 1.

Nanotechnology – What does it mean?

By Dr Nicholas Derry

Many older children enjoy playing with Lego Technic, the form of Lego which uses often tiny parts to produce complex models, capable of performing a variety of tasks. To give a Lego Technic model to a very young child would be unlikely to result in the child correctly assembling the parts in the correct order. To be able to build such models requires a degree of manual dexterity that young children do not have. Until recently humans have acted very much like young children in the way we have attempted to manipulate materials to give us the properties required. Often this attempted manipulation has been very much hit and miss; consider alloys, where atoms of different metals are mixed together in a variety of ratios in the hope of providing a new material which combines the best of all the component elements. Sometimes the combination produces a material that behaves like plasticine, sometimes a useful new material results. Nanotechnology offers the potential to construct new materials in the same way an older child builds a complex Lego Technic model, by the manipulation of tiny parts, in this case individual atoms, to form complex structures.

While the practicalities of moving around individual atoms to make new structures has only been possible in the last 20 years or so, its potential was predicted by the Nobel prize winning physicist, Richard Feynman. In a speech given to the 1959 annual meeting of the American Physical Society, Feynman suggested that while nothing in the laws of physics prevented us from rearranging atoms the way we wanted, such changes could not then be made because of technology constraints. The development of instruments such as the atomic force microscope (ATM) and scanning tunnelling microscope (STM) in the 1980s proved to be the trigger, allowing some of what Feynman had predicted to occur.

Nanotechnology is the application of nanoscience. The term was first coined by Norio Taniguchi in 1974, when discussing the ability to engineer materials precisely at the nanometre scale. During the 1970s the electronics industry provided the primary driving force for miniaturisation, as it strove to fit increasingly complex electronic circuits onto ever smaller silicon chips, in order to increase the capacity of the device. More recently, nanotechnology has been defined by the Royal Society as '… the design, characterisation, production and application of structures, devices and systems by controlling shape and size at nanometre scale.' ('Nanoscience and nanotechnologies: opportunities and uncertainties' Report of the Royal Society and The Royal Academy of Engineering, 29 July 2004). For this reason it is better to consider this technology in the plural, as nanotechnologies. There can be no single field of nanotechnology, as it can and does involve overlap between a wide range of more traditional sciences, such as biology, chemistry and physics.

Nanoscience is the science of very small particles, generally defined as particles less that 100 nm (10^{-9} m) in diameter. To give an idea of just how small nanoparticles are, were a 100 nm diameter nanoparticle the size of a tennis ball, a red blood cell would have a diameter of 13 m and a human hair 65 m. At the nanolevel, materials can have significantly different properties in comparison with the same material at a larger scale due to surface and quantum-size effects. At this scale, the proportion of atoms that are on the surface of the particle becomes significant. A 30 nm particle will have 5% of its atoms at the surface, a 3 nm particle 50%. The result of the number of atoms at the surface is that nanoparticles have negligible inertia, while exhibiting significant viscosity; a nanoparticle moving through a liquid can be thought of as being equivalent to Ian Thorpe trying to swim through treacle. The nanolevel also marks the point where quantum mechanics begins to take over from classical mechanics in describing atomic structure. This can cause significant changes in the physical properties of the materials, while leaving the chemical properties unchanged. For example, previously opaque materials may become transparent, stable materials may become combustible, solids become liquids and insulators, conductors. Nanosize particles can also be a different colour to the bulk material. For example, gold nanoparticles are reddish in colour, not yellow. This is due to the fact that in a gold nanoparticle the movement of the electrons is more restricted than in a gold macroparticle, impacting on the frequency of light absorbed by the electrons. This can be equated with shortening a string on a musical instrument resulting in the note sounding at a higher pitch. The analogy can be taken a step further in that a stringed instrument, such as, a guitar only has a certain number of notes that it can play, just as the electron arrangement of an atom is defined, which means that the number of available colours for an element is strictly controlled.

Presently, there are two ways in which nanomaterials can be manufactured. ‘Bottom-down’ nanotechnology, sometimes called molecular nanotechnology, involves building materials atom by atom. At present, this is a very slow process, utilising sophisticated instruments such as the ATM and STM. These tools use nanoscale probes that are capable of picking up, dragging or sliding atoms or molecules around, resulting in the assembly of more complex structures. One of the most famous examples of this technology in action was demonstrated in 1990 when two scientists at IBM moved xenon atoms around on a nickel surface to spell out IBM. It took them a day under strictly controlled laboratory conditions. Nature already makes extensive use of ‘bottom-down’ nanotechnology, building complex molecular structures from atoms or simpler molecules, a process that often involves self-assembly of such structures. For example, many viruses self-assemble nanoscale particles to produce functional viral particles. The challenge of this method is to produce structures quickly enough and of sufficient quality. ‘Top-down’ nanotechnology has a much more traditional feel to it, using some long standing engineering techniques, such as micro- and nano-lithography and etching, to produce structures at the nanoscale. The challenge in this form of nanotechnology is to maintain the required accuracy at such a tiny scale. In reality, the two techniques have now reached a point where both are producing structures of a similar scale, leading to increasingly novel methods of fabrication involving hybrid techniques.

In some senses nanotechnology is not a new technology. Nanoparticles of gold and silver have been used for centuries as coloured pigments for stained glass and ceramics. The budding nanotechnologists of the Middle Ages faced the same problems as their modern day counterparts; trying to ensure consistency in particle size, as colour changes with the size of the nanoparticle. The electronics industry has been using nanotechnologies for decades to produce ever smaller components. Polymer scientists have been designing polymers with ever more specific properties by linking together nanoscale monomer units. Nature makes wide use of nanoparticles; spider silk protein, nanoscale colloid particles in milk and the wide range of protein structures that control the biological processes in living organisms.

While there are examples of nanotechnology currently in commercial use, there are many more with significantly longer timeframes in terms of their commercial release to the public. Essentially, these nanotechnologies are based on nanomaterials; including nanotubes, nanoparticles and nanostructured surfaces, and bionanotechnologies; including biological sensors, drug delivery systems and the use of nanoparticles to improve body imaging techniques.

Carbon nanotubes were first observed in 1991. Only a few nanometres in diameter, up to a millimetre long and consisting of a single layer or multiple layers, they are essentially closed graphite sheets. Nanotubes are the focus of a great deal of research because of their chemical and physical properties. They are significantly stronger than steel, which together with their low density makes them potentially very attractive as materials for use in the aerospace industries. They conduct heat and electricity better than many metals. Nanotubes have potential in a range of applications, including composite materials, enhancing polymer conductivity and nanoelectronics.

- CSIRO is currently involved in developing a commercially viable process for the production of carbon nanotubes:
  www.csiro.au/csiro/content/standard/ps7s,,.html

- At Queensland University of Technology, Professor Nunzio Motta and Dr Eric Waclawik are working on a new breed of solar photovoltaic cells which employ nanothick polymer layers. Light hitting the polymers causes electrons to be knocked free and inserting nanotubes into the polymers acts to channel the electrons through the polymer. This research has the potential to provide an alternative to the heavy, delicate and expensive silicon solar cells. The thickness of the polymer sheets allows for great flexibility; at 10% efficiency, four pieces of polymer the size of an A4 sheet could supply a laptop with the electrical energy it needs.
  http://renewableenergyaccess.com/rea/news/story?id=42103

Nanoparticles are of particular interest because of their new properties, compared to macroparticles of the same material.

- Nanoparticles of zinc oxide and titanium oxide are now used in sunscreens. At the macroscale, the particles produce the effects often seen on the faces of well known sporting stars. At the nanoscale, the particles become transparent, while still retaining their ability to absorb ultraviolet radiation. This has allowed their inclusion in a wide range of cosmetic products, such as face cream, providing protection from the sun throughout the day.

- Tungsten-carbide-cobalt nanoparticles can provide a coating as hard as diamond. The result is greater resistance to wear than more conventional materials in applications such as drill bits, cutting tools and jet engine components.

- Associate Professor Besim Ben-Nissan of the University of Technology, Sydney is working on a nanoparticle-based synthetic bone derived from hydroxyapatite
  www.future.org.au/news_2006/june_july/tt.html

- In the future, synthesis of polymer coated nanoshells has the potential to enable the delivery of drugs to specific target sites within the body, thus allowing doctors to use significantly reduced doses, with all its attendant benefits in terms of reduced side-effects from drugs.

Other, more specific examples of the application of nanotechnologies include:

- Transdermal drug delivery. This involves the use of nanosized protrusions on the underside of patches that would be fixed to the skin like a band aid. The protrusions carrying doses of the drug, act as tiny hypodermic needles, releasing the drug, which can then pass to other parts of the body via the tissue fluid. This is being considered for use in the delivery of vaccines as well as drugs. For an animation of this application go to:
  www.nanovic.com.au/index.php?a=industry_focus.drugdelivery&p=186

- Nanocoatings have resulted in self cleaning glass, glass that can become transparent or opaque according to the current applied to the coating and a light activated, self-cleaning glass for aquariums. For an animation of this application go to:
  www.nanovic.com.au/index.php?a=industry_focus.building&p=190

- Materials such as NanoTex resist stains and liquid spills. This fabric is already used by Kathmandu and King G in a range of products.
  www.nanovic.com.au/index.php?a=industry_focus.textile&p=23

- Dressings containing nanoparticles of silver take advantage of the considerable antibacterial property of silver. At the nanoscale, those antibacterial properties are considerably enhanced.
  www.azonano.com/details.asp?ArticleID=1695

- Nanostructured materials are being investigated as potential electrodes in both batteries and fuel cells. In batteries, such materials offer the prospect of significantly improved power density, durability and recharge capacity, while in fuel cells, nanostructured electrodes are under development. Nanotubes also offer the possibility of providing a hydrogen storage system for use in fuel cells.
  www.azonano.com/details.asp?ArticleID=1339

The next few years holds out the possibility of more active nanostructures, capable of changing size and or shape during use. Further in the future comes the potential of systems of nanostructures self assembling complex structures that might be used for bone repair and tissue repair.

There has been concern expressed that particles at the nanoscale may pose a significant health threat. The very fact that these particles are so small as to be invisible makes them harder to remove from an environment. Certainly, nanosize particles are small enough to pass across many of the membranes that currently serve as a barrier to larger sized particles. While engineered nanoparticles are a recent innovation, humans have been exposed to incidental nanoparticles for centuries. Burn a piece of toast and you will be inhaling nanoparticles, not to mention the particles generated by activities such as welding and cutting metal, and by the internal combustion engine. There is an understanding that current safety and risk assessment frameworks need considerable adaptation for use with nanotechnologies. While there have been studies on the health effects of exposure to nanoparticles, the results have as yet been non-conclusive. For many materials there is no reason to expect there would be a health hazard. For example, as a piece of charcoal is not toxic to humans, neither should nanoparticles of carbon, as there is no change in the chemical properties of the material. However, nanoparticles may be able to take part in biochemical pathways and processes to an unforeseen extent, which may in itself lead to some degree of toxicity. While there are many in the field who believe that there is a need to further fund research into the potential toxicity of these newly developed nanoparticles, few would believe in the possibility of a world over run by self-replicating nanobots, the so-called ‘grey-goo’ described by Eric Drexler in his 1986 book, *Engines of Creation*.

Nanotechnology is to the early twenty-first century what biotechnology was to the 1980s, a fact that governments around the world have recognised. Research and development funding has increased significantly in the last few years, from US$1 billion in 2000 to US$4.5 billion. In Australia, government and private funding of research groups totals $100 million. As of 2006, there are 70 research groups working in the field, with 50 nanotechnology companies, 30 of which have begun operation in the last five years. These companies are focused on developing or producing nanotubes, nanopowders, nanofibres, ceramic particles and nanodots. In Victoria, Monash University, Swinburne University of Technology, RMIT University and CSIRO, together with the Victorian Government have established Nanotechnology Victoria to ensure effective commercialisation of the products of nanoscience research. Fully developed, there will be almost no aspect of our daily lives that will not involve some form of nanotechnology.

References

Websites

BigPicture: Nanotechnology
www.wellcome.ac.uk/node5954.html

Nanotechnology and Nanoscience, The Royal Society, The Royal Academy of Engineering
www.nanotec.org.uk/

Nanotechnology: It's a Small, Small, Small, Small World, RC Merkle.
www.actionbioscience.org/newfrontiers/merkle.html

National Nanotechnology Initiative
www.nano.gov

Review of up to date nanotechnology applications
www.nanotech-now.com
www.azonano.com
www.nanovic.com.au

www.investaustralia.gov.au/
Provides information on Australian commercial nanotechnology applications.

CD-ROM

Chemistry: a pathway to the Emerging Sciences in Victoria (VCAA & DIIRD)