Giants of the Infinitesimal:

an interactive experience of the Nanoworld

Teachers' notes with questions, answers and curriculum links

KS4 and A Level

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Nanoscience could revolutionise everything in our world, including healthcare, computers and energy sources. This interactive exhibition presents cutting-edge nanoscience research. You can try large-scale models to find out how scientists explore the world at the nanoscale to create completely new nano structures. The exhibition is a unique collaboration between artists and scientists which enables you to visualise the invisible.

You will be introduced to a completely new and strange world – the Nanoworld!

The exhibits:

Entering the Nanoworld – Nano-sized particles are very, very, very small. Light cannot be used to see nanoparticles so highly specialised scientific techniques are required to explore this world (exhibits 1 and 2). Scientists are not only able to image these minute particles; they are able to move them individually to form new structures (exhibit 3). Nature is much better at this than the scientists and self-assembly has been occurring over millions of years to form complex structures, such as chlorophyll, on which our lives depend (exhibit 4). Artists' models enable us to glimpse this nanoworld (exhibit 5).

Exhibit 1a	Investigation chamber – using X-rays to find which elements are in a sample. Can you track the X-ray and the electron beams they generate?
Exhibit 1b	Investigation chamber – using Infrared (IR) radiation to determine molecules present in a sample. Look at the IR spectrum of water and carbon dioxide. Can you see how the IR pattern of absorption is very different for each molecule? This allows us to tell them apart.
Exhibit 2	Electron microscope – using electrons to image. Challenge - can you scan the sample and see what is it?
Exhibit 3	Scanning Probe Microscope (SPM) – single atoms can be positioned individually. Challenge - make a nanowire out of a line of atoms before it gets too hot!
Exhibit 4	Self-Assembly Pool – watch the molecular dance responsible for assembling molecules in nature. Can you spot structures such as linked rings forming?
Exhibit 5	Complexity – visualising the amazing structures of the Nanoworld. Graphene kinetic sculpture. The vibrations simulate sound travelling through the graphene.

Giants of the Infinitesimal Exhibition – Museum of Science and Industry Manchester

Introduction

Nanometres are very, very, very tiny. There are a million nanometres in a millimetre and a billion nanometres in a metre so it is difficult to imagine anything that small.

1000,000 nanometres = 1 millimetre

The thickness of a piece of paper is about 1/10th of a millimetre. This means it is about 100,000 (hundred thousand) nanometres thick!

A human hair grows at about 1 nanometre per second.

We can see fine sand particles that are about 1/100th of a millimetre thick. But when we try to look at much smaller particles we cannot see them using our eyes. This is because our eyes use visible light to see. The object we are looking at reflects light which then enters our eyes where it is detected by the retina at the back of the eye. Signals are sent to our brains – so we see.

Visible light is an electromagnetic wave. The wavelength of visible light varies between about 400 nanometres for blue light and 700 nanometres for red light (0.4 to 0.7 micrometres). If we try to see a nanoparticle using visible light, then the wave is about 1000 times too big. **LIGHT IS TOO BIG! *It would be like feeling for a pea with a dumper truck.***

When scientists investigate nano-sized particles, including individual atoms and molecules, they use very special techniques to image, move and interrogate the nanoworld.

In this exhibition artists have worked with nanoscientists to create activities so that you can learn about and try techniques that the scientists use to visualise the invisible. They have also created sculptures so that you can glimpse the amazing complexity of the nanoworld.

Questions:

1. How many nanometres are there in 1 millimetre?
2. How many nanometres are there in a metre?
3. How many nm^3 are there in a cm^3?
4. Can we use our eyes to see nano-sized particles?
5. Why not?

Curriculum links: Units of length
Electromagnetic spectrum

Exhibit 1a and 1b: The Investigation Chamber – (Ultra High Vacuum Chamber)

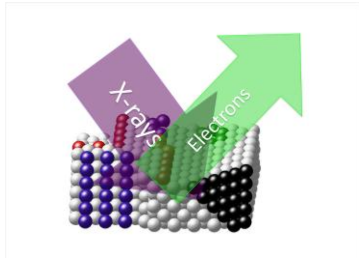
This is a real piece of specialised scientific equipment which has been used by scientists to find out about the Nanoworld. The Investigation Chamber was attached to the Synchrotron at Daresbury Laboratory CCLRC, Cheshire, and was used for many experiments. The sculptors have cut away sections so that you can see inside.

Giants of the Infinitesimal Exhibition – Museum of Science and Industry Manchester

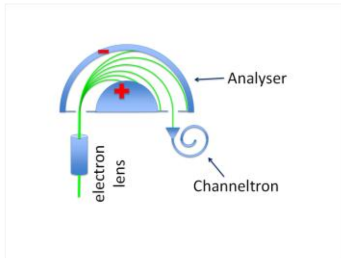
Scientists used beams of X-rays or infra-red light in the investigation chamber. Experiments using this equipment were performed under ultra-high vacuum. The vacuum in the investigation chamber was so good that it was comparable to that found in outer space. This was necessary so that the surfaces do not get dirty from the air and the air particles do not stop the electrons.

Exhibit 1a: Using X-ray beams to identify which atoms are present in a sample:

A beam of intense X-rays are directed at a sample of material. The X-rays excite the atoms in the sample so that they give off electrons. This is the photoelectric effect explained by Einstein at the start of the 20^{th} century. There is such a good vacuum in the chamber that the electron beam is able to travel to the analyser without hitting any air molecules.

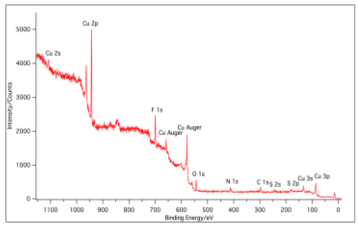


Note: *the X-ray beam and the electron beam are represented by the yellow tracks that you can see through the windows that have been inserted in the exhibit. Press the button for the track to light up.*



In the analyser the electrons pass through an electric field which forces them to move in a circle and spreads them out according to how fast they are going. You can see the curved tracks. The speed of the electron depends on its binding energy in the atom from which they originated (i.e. the energy needed to "kick" them out of the sample.) The channeltron measures the number of electrons having a certain speed. From this measurement we can work out the binding energies of the electrons. *(Can you spot the channeltron?)*

The peaks indicate the different elements



The binding energy tells us which elements are on the surface. Therefore by plotting the number of electrons (y-axis) against their binding energy (x-axis), the elements can be found from the resulting graph (which is known as a *photoemission* spectrum) obtained. Samples of photoemission spectra for specific elements are shown on the Perspex sheets attached to the chamber. Use these to analyse the unknown samples.

Questions:

1. What are X-rays?
2. What are given off when the X-rays hit the sample in the investigation chamber?
3. Do they all have the same energy
4. How do scientists find out which elements are on the surface from the graph (spectrum).

Curriculum links: X-rays - high energy electromagnetic radiation
Vacuum
Photoelectric effect and binding energy

Exhibit 1b: Using infra-red beams to identify molecules:

Note: *you can trace the path of the infra-red beam by looking through the windows and following the red tracks.*

The chemical bonds between the atoms in a molecule can be thought of as tiny springs. Indeed, Einstein himself used a simple ball-and-spring model to explain just how atoms vibrate in molecules and crystals. The upshot of the springiness of the bonds is that molecules constantly shake and "shiver". They can vibrate in very many ways e.g. by stretching and contracting their bonds, or by changing angles between atoms (e.g. by bending, rocking or twisting) – the larger the molecule, the greater the variety of molecular vibrations.

The infra-red beam in the investigation chamber is made up of a range of different wavelengths of light. Another way of thinking about this is that there are lots of different *frequencies* of the infra-red light – the frequency is just the number of full cycles of the wave that happen in 1 second. When the frequency of the IR light matches the rate of a particular molecular vibration (i.e. the number of times per second the molecule vibrates back and forth) then the light is absorbed. Scientists use a special type of unit called the wavenumber to account for the frequency of the light – this is what's plotted on the x-axis of the graph.

The key point is that when the IR beam reaches the detector, the infra-red absorbed at different frequencies can be measured. A graph is plotted from which the molecules of the sample can be identified. The frequencies that are absorbed by a specific molecule are like 'fingerprints' – i.e. the shape of the graph is unique for each type of molecule so the molecules in the sample can be identified.

Note: The infra-red light is not used to directly see the molecule. Instead it is used to make atoms in the molecule vibrate at the frequency of the infra-red. The scientists plot a graph of the results.

Questions:

1. What is infra-red light?
2. Electromagnetic radiation can be thought of as waves. What is the approximate wavelength of the waves?
3. In this type of experiment do all the infra-red rays have the same energy?
4. What happens to some of the infra-red light when it hits the sample?
5. Why does this happen?
6. In which ways can the molecules vibrate?
7. You will find graphs showing the absorption of infra-red by different molecules. Try matching them with the examples given to find the elements present.

Curriculum links: Infra-red radiation.
Chemical bonds
Molecular vibrations - Kinetic theory
Spectra

Exhibit 2: The Electron Microscope

An optical microscope uses visible light which is passed through a series of lenses. An electron microscope uses a beam of electrons to scan very, very small objects and uses a computer to build up an image from the measurements obtained. Electron microscopes can be used to form images of molecules. A beam of high energy electrons is focussed by magnetic lenses to a very fine point. Scanning coils move the beam of electrons backwards and forwards across the object so that the beam scans the object. As the electron beam hits a point on the object, other electrons are knocked from the surface. These electrons are counted by a detector and the information is used to build up an image. This appears as black and white because each point on the image represents the number of electrons from each point on the object. The electrons knocked out from the sample would be absorbed if they were passed through air and not reach the detector. Therefore there is a vacuum inside an electron microscope. Consequently samples have to be prepared so that they can withstand the vacuum.

Exhibit 4 is a model which enables you to scan objects and build up an image. As you move the joystick sections of an object can be seen. As you scan side to side and up and down the image of the object builds up. You have one minute to work out what it is. *(The answers are on the back of the exhibit.)* There are several objects so if you did not guess one; you can try another.

Questions:

1. Why is light generally unsuitable to image nanoscale objects?
2. Electrons are absorbed when they collide with air molecules. How is this problem overcome in an electron microscope?
3. Visible light can be focussed by passing the light through a lens. How is the beam of electrons focussed
4. What happens when the beam of electrons hits the surface of the object?
5. Why are high energy electrons used?
6. How is an image formed?

Curriculum links: Electron microscope
de Broglie wavelength

Exhibit 3: The Scanning Probe Microscope (SPM)

A scanning probe microscope (SPM) is a microscope like no other. Unlike the traditional microscopes you're familiar with (and, indeed, the electron microscope described in the notes for Exhibit 2), an SPM doesn't use lenses or mirrors or any type of optics to form an image. Instead, an SPM uses an ultra-sharp probe – so sharp that it ends in a single atom or molecule – to build up an image of the nanoworld. Just to give you some idea of scale, the SPM probe is equivalent to a table tennis ball stuck at the end of the Matterhorn, one of the highest mountains in the Alps. The point is so small that it is an up-side down pyramid ending in a single atom at the tip.

When the tip is moved very close (within a few nanometres) to a surface then a variety of forces and effects come into play. For example, a small electrical current (arising from a weird quantum physics effect called tunnelling) can start to flow and/or a chemical bond can form between the tip and the sample. The tip of the SPM is then moved back and forth across the surface and either the tunnel current or the chemical force is monitored. (There are lots of forces that could contribute {e.g. due to magnetic fields} but we don't need to go into those). Because the tip is only one atom across then it is capable of measuring changes in current or force right down to the atomic level. From these atomic-scale variations in tunnel current or chemical force experienced by the tip it is possible to generate an image of the atoms at the surface.

Not only can an SPM see atoms, it can move them! The force between the tip and an atom (or molecule) at the surface can be tuned so as to push, pull, or even pick up single atoms. This type of atomic-scale engineering was pioneered by Don Eigler and his colleagues at the IBM research labs both in the US and in Switzerland. A variety of different artificial structures, never before seen in Nature, have been formed by positioning atoms one at a time on a surface. (See the website http://www.almaden.ibm.com/vis/stm/gallery.html) One of the research groups involved with the Giants of the Infinitesimal exhibition has used atom manipulation of this type to flip the smallest possible toggle switch. (See www.sixtysymbols.com/toggleswitch.htm)

The SPM exhibit shows how atomic manipulation works in practice. The challenge is to build a line of atoms, one at a time, before the sample and tip get too hot.

All atoms are in constant motion caused by the heat energy they possess. The higher the temperature, the more energy the atoms have. The coldest temperature - absolute zero - is 0 Kelvin (about - 273 Celsius). This is very, very cold; your freezer is at about – 20 degrees Celsius! Near to absolute zero, the atoms are almost still. The inside of a real SPM is at a very low temperature because the scientists are able to manipulate atoms much more easily than at room temperature. As the temperature increases the heat energy increases and the atoms move more violently so it becomes increasingly difficult to manipulate atoms.

Exhibit 3 is a model of a SPM in which the balls represent atoms. You can steer the probe in the exhibit using the buttons so that it is over an 'atom'. The probe can be lowered to attract the 'atom' with its tip. Then the probe can then be relocated and the 'atom' released to take up position within a line to make up a nanowire. When you have completed the nanowire all the lights in the wire will flash.

You have five minutes to make the nanowire. After that time, the SPM begins to 'warm up' and becomes pink. You will see the balls start to move around so that it is very difficult to manipulate the 'atoms'. Then as the temperature rises further the atoms vibrate violently and it is impossible to manipulate them. The SPM will be glowing red.

Can you make a nanowire before the temperature begins to rise?

Questions:

1. Why are the experiments conducted at very low temperatures?
2. How small should the tip of the probe be, ideally?
3. How can scientists produce an image of a surface using an SPM?

Curriculum links: Kinetic theory and the temperature dependent movement of atoms
Absolute zero

Exhibit 4: The Self-Assembly Pool - nanoparticles can spontaneously form completely new structures.

Atoms and molecules attract each other by the forces that exist because of their electrons. This attraction leads to 'Self-assembly'.

It is the balance of attraction and repulsion between the electrons in different atoms which decides which particular shapes and structures can be formed via self-assembly. The forces between atoms are continually disrupted by the movement and vibration of atoms and molecules due to energy in the form of heat. This heat energy, while at first appearing to be just a nuisance, is essential for the process of self-assembly – it allows atoms to find their most stable bonding position in a structure. It also allows atoms to make and break bonds, so the structures formed can often evolve into new and different shapes.

Over millions of years complex structures have formed by self-assembly. The double-helix structure of DNA is a famous example. Another example is chlorophyll which traps sunlight to provide energy for food. All living things have complex proteins that self-assemble into complex shapes in 3D, which control their function in a cell. Scientists are able to form images of these complex structures which are essential for life itself. Many of the structures are beautiful patterns.

Scientists are working to develop completely new structures designed for specific tasks. Also their understanding of the amazing structures created in nature is increasing. Nature is much better at making complex structures!

As our knowledge of the nanoworld increases many of the major world problems might be tackled using new forms of nanotechnology. Controlling nanocomponents lies at the heart of the clean harvesting of solar energy, the development of new smart materials and the realisation of entirely new concepts in computing. Computers may become thousands of times smaller than at present and also thousands of times faster!

Exhibit 5: visualising the amazing complexity of the nanoworld – see also our website.

The artists in the Giants of the Infinitesimal team have created sculptures to represent nanoscale structures which are fascinating yet beautiful. Porphyrins are molecules that have developed naturally over millions of years and our lives depend on them. They are the basis of red blood cells and chlorophyll. The carbon nanotubes have been developed by scientists.

Recently, carbon 'buckyballs' and carbon nanotubes have been developed by scientists. Graphene is another allotrope of carbon. The structure of graphene is an atomic-scale honeycomb lattice made up of a single layer of carbon atoms. In other words it is a carbon crystal which is only one atom thick. Andre Geim and Konstantin Novoselov, both at the University of Manchester, shared the Nobel Prize in Physics last year for their work on graphene. The exhibition includes a large Graphene Kinetic Sculpture which flexes intriguingly. If you watch carefully you can see a wave of vibration moving through the graphene, this is called a phonon (it is how sound travels through a solid). Konstantin Novoselov attended the launch of the exhibition and sat beneath the graphene model!

See also the interactive digital graphene sheet at http://www.giantsoftheinfinitesimal.com/digital-graphene.htm. You can change the elasticity, the number of atoms and other variables. If you switch off the lines which represent the bonds, the effects are even better.

Curriculum links: molecular structures

Answers to questions:

Introduction

1. 1000,000
2. 1000,000,000
3. 10^{21}
4. No
5. Light waves are too big.

Exhibit 1a: The Investigation Chamber - X-ray beams

1. High energy electromagnetic waves.
2. electrons
3. No. The energies depend on the elements in the sample.
4. The peaks in the binding energy values indicate the individual elements present.

Exhibit 1b: The Investigation Chamber - infra-red beams

1. Electromagnetic radiation
2. Wavelengths are about 700 nanometres – i.e. much lower energy than X-rays.
3. No.
4. It is absorbed.
5. The frequency/energy of some of the waves is just correct to be absorbed because it matches the frequency/energy of molecular vibrations.
6. By stretching and contracting their bonds (like a spring), or by changing angles between atoms (e.g. by bending, rocking or twisting).

Exhibit 2: The Electron Microscope

1. Wavelength too large.
2. The electron microscope has a vacuum inside it.
3. By passing the electrons through a magnetic field. Can also be an electrostatic field.
4. Electrons are knocked off and X-rays are created.
5. So they have sufficient energy to excite the atoms at the surface of the sample so that electrons are emitted.
6. The beam is moved backwards and forwards across the surface and the number of electrons from each point is counted by a detector. A computer then combines the vales to produce an image.

Exhibit 3: The Scanning Probe Microscope (SPM)

1. So that the movement of the atoms is minimised.
2. The tip should be made of one atom.
3. They move the tip back and forth, monitoring the variation in chemical force or electrical current as it scans the surface.