Physics Factsheet

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Models in Physics

The purpose of this Factsheet is to explain the concepts of Models in Physics – their use, significance and limitations. Before studying the Factsheet, you should make sure that you are familiar with the Rutherford Scattering Experiment and the Kinetic Theory Model from your GCSE course. These are two important examples of the use of models.

More detailed discussion of the Kinetic Model is given in Factsheet 25.

There is not a specific topic devoted to models on most AS or A2 specifications, but questions about the Rutherford Scattering Experiment, Kinetic Theory, or other examples where a model is important, are likely to call for understanding of the use and limitations of models. There could also be questions involving models on Edexcel PHY 6, the Synthesis Paper.

What is a model?

The word "model" is used in every-day speech to mean a smaller version of a real object, but the word is used in Physics with a more specialised meaning.

A model is a set of ideas which help to explain a physical system. The model is a **simplified description of one aspect of reality.**

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Using models in Physics

Models are extremely useful in Physics. They help us to summarise and describe the current understanding of many systems.

Physicists make observations and then suggest a set of ideas which describe the situation. This is the basic model. Because physical systems are usually complex, it is normal to **make simplifying assumptions** as part of the model. Thus a model is never a perfect explanation.

The model is then used to make predictions of how systems would behave. Investigations are carried out to see if the data collected agree with the predictions of the model. Provided the data fit the model, then the model continues to be the accepted view of the system, but whenever new data, which do not fit the model are collected, the model must either be modified, or augmented or, in the worst case, abandoned in favour of a new model. This is how scientific progress is made.

The use of models is central to the development of scientific knowledge.

> A model expresses the current state of understanding of a particular system. It is not relevant to ask if a model is true, but rather, if it is useful. The use of models is central to the development of scientific knowledge.

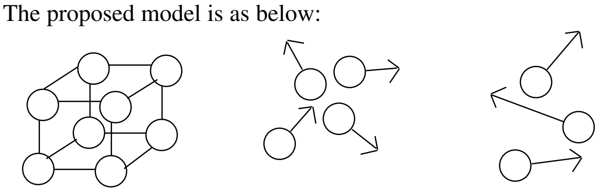
Kinetic Theory Model as an example of the development of a model

The Kinetic Theory model for solids, liquids and gases, provides a very good vehicle to look at the principles of the development and use of models in physics.

Scientists noticed that liquids, such as water, could change easily from liquid water to solid water (ice) and to gas water (water vapour). This suggests that it is the **arrangement** of the particles, not the particles themselves, which are responsible for the different properties of solids, liquids and gases.

The next step in the procedure is to propose a model which accounts for simple observed properties of solids, liquids and gases i.e. that solids keep their own shape, liquids flow and have a surface and gases completely fill any container they are put in.

The proposed model is as below:



solid	liquid	gas
* close together	* about the same	* far apart
* held by bonds	* no fixed bonds	* completely free
* in a regular pattern	* no pattern	* no pattern
* can only vibrate	* free to move, but still pull on each other	* moving fast

These simple ideas constitute the basic model and fit with the observed properties mentioned above. The model can be tested to see if it also fits other observed behaviour e.g. gases are easily compressed into a smaller volume, solids and liquids are difficult to compress, solids melt into liquids at a specific temperature, liquids evaporate into gases, evaporation takes place at all temperatures, rate of evaporation increases with temperature, with surface area, and with draught.

It can also be used to predict behaviour which can then be tested. e.g. the effect of evaporation on the temperature of the remaining liquid.

> ***Worked example:***
> ***Use the simple ideas of the kinetic model to predict the effect of evaporation on the temperature of the remaining liquid.***
>
> *The kinetic model suggests that the particles in a liquid are close together but free to move. At any given temperature, the particles will have a range of speeds, and be travelling in many different directions. Every now and then a particle will approach the surface of the liquid travelling fast enough to escape the attraction of surrounding particles. This particle has now become a gas particle. Since it is the fastest particles which escape, the average speed of the remaining particles is reduced. The average speed is related to the energy and thus the temperature of the liquid. So the Kinetic theory model predicts that evaporation cools the remaining liquid.*

This prediction has added another key idea to our model: that the average speed of the particles is related to the temperature.

Mathematical aspects of models
If the model can be made quantitative instead of just qualitative, so much the better. In the case of the Kinetic Theory model, this is achieved through considering the change in momentum of a particle as it hits the walls of the container, averaging over lots of particles and thus arriving at expressions for the pressure of a gas on its container. Agreement between these expressions and experimental observations is powerful evidence for the usefulness of the model. See Factsheet 25 for details of the mathematical predictions of the kinetic theory.

Limitations of the KT model
Since models are a simplified description of some aspects of reality, predictions can never be expected to be fulfilled precisely by experimental data. A good model can account for the discrepancy between the theory and the experimental results. Kinetic theory also illustrates this idea well.

Kinetic theory for gases predicts that:

$pV = 1/3nm\langle c^2\rangle$ *where* p = *pressure,* V = *volume,* n = *number of particles,* m = *mass of each particle (i.e. nm/V is the density* ρ *of the gas.)*

The fact that $\langle c^2\rangle$ is related to the temperature of the gas leads to the expression:

$pV = RT$ *for each mole of gas*

This is essentially the Ideal Gas Equation (incorporating Boyle's Law and Charles Law.)

Precise experimental data reveals some deviations from the theoretical prediction. This can be reconciled with the theory by recognising that certain simplifying assumptions were made in the formulation of the model. These assumptions are:

- there are many particles in the gas, so that average behaviour is representative of the whole.
- the particles are moving rapidly and randomly.
- the behaviour of the particles can be described by Newtonian mechanics.
- the particles are far apart (compared to their diameters), and have no pull on each other.
- any forces acting do so only during collisions, and then only for a short time compared to the time between collisions.
- the particles themselves occupy negligible volume compared to the volume of the gas.
- the collisions are elastic (K.E. is conserved).

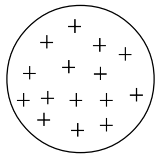
It is the extent to which these assumption hold in practice, which determines how useful the model is. In the case of the Kinetic Theory model, most of the assumptions hold well and so the model is useful. To get a better match, a more sophisticated version of the model can modify the equation to take account of the discrepancies.

If the predictions of a model are used in circumstances where the assumptions of the model are not valid, then the predictions will not be valid either. There is always this limitation on the use of models; they must be treated with caution and always in circumstances in which the assumptions of the model are valid.

A model is only useful within the limitations of its simplifying assumptions.

When the existing model cannot explain new data
It might be thought that if new data cannot be explained by a model, the situation is dire, but, in fact, occasions on which this has happened have led to some of the most important advances in science. The Rutherford scattering experiment is an important example of this.

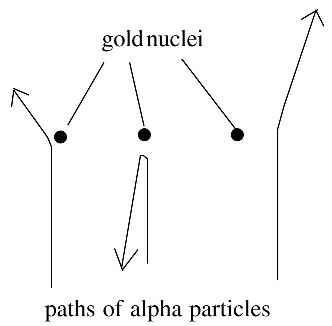
The accepted model at the time of the scattering experiments carried our by Geiger and Marsden was the " plum pudding model" also called the "currant bun model" in which the charges which formed the constituents of the atom were described as being uniformly distributed throughout the atom.



Geiger and Marsden used the model to predict the pattern of the deflection of helium nuclei (alpha particles) scattered from a very thin gold foil. When the experiment was performed, most particles were deflected as predicted, but there were some which were deflected through much larger angles than expected, indeed some were deflected through almost 180^0. This was completely inexplicable using the model and Rutherford realised that no amount of tinkering with the model or adding to it could predict the observed data. He suggested that the only explanation which would account for the data was that all the positive charge and most of the mass of the atom must be concentrated in a very small region at the centre.

Although this was a strange suggestion and would probably not have arisen spontaneously, it could give an explanation. Rutherford, Geiger and Marsden made detailed predictions, quantitatively, to fit in with the observed data and calculated the relative size of this small region – "the nucleus", to the size of the atom. Thus was born the "nuclear model of the atom".

Paths of alpha particles scattered by gold atoms



Evidence to support a model
Sometimes, rival models can explain some data equally satisfactorily, while one crucial piece of evidence would separate the two models. Until this data becomes available, then each model has its supporters. This situation occurred with the rival models of transmission of light. Newton was convinced that it travelled as a stream of particles, while Huygens believed it to be a wave. Both models could predict reflection and refraction, but to fit with the observed direction of refraction in a denser medium, the particle model required light to travel faster in a denser medium, whereas the wave model required light to travel slower in the denser medium. Unfortunately, that evidence was not available at the time. Newton was the more famous scientist, and the stronger character so his model became accepted. It was quite some time before the speed of light in a medium like glass was measured and shown to be less than the speed in air, supporting the wave theory.

Sometimes a crucial piece of evidence can support one rival model as opposed to another, but that evidence is not always available at the time the models are proposed.

Another example of evidence to support rival models, is in the case of the Big Bang model of the origin of the Universe as opposed to the Steady State model. Initially the Steady State model seemed the more sensible and likely, but several pieces of evidence, e.g. red shift of light from distance stars, and the microwave background radiation, fit better with the Big Bang model than with the Steady State. Factsheet 51 gives details of the red shift evidence.

Typical Exam Question

According to the kinetic model, the pressure p of an ideal gas is given by the equation

$$p = 1/3\ \rho <c^2>$$

where ρ is the density of the gas and $<c^2>$ is the mean squared speed of the molecules.

(a) Give 3 assumptions of the kinetic model. (3)

(b) Express ρ in terms of the number of molecules N, each of mass m, in a volume V. (1)

(c) Use the idea that the mean K.E. of a molecule is proportional to the Kelvin temperature T, plus your answer from b) to show that, within the assumptions of the model, p is proportional to T. (3)

(d) To what extent do the assumptions of the model hold in relation to real gases. (3)

Answers:

(a) Any 3 of the assumptions given in the text.

(b) ρ = total mass/volume, so ρ = Nm/V

(c) If k.e. is prop to T, then ½ m$<c^2>$ is prop to T.

$p = 1/3\rho <c^2>$ may be written

$$p = \frac{1/3Nm<c^2>}{V} = \frac{2/3\ N}{V} \times (1/2\ m<c^2>)$$

Since N, m and V are constant for a given mass of gas at constant volume, this gives that pressure is proportional to Kelvin temp. for a given mass of gas at constant volume and within the assumptions of the model.

(d) No gases behave as "Ideal gases", but most gases approximate well to ideal gases, particularly in the normal, as opposed to extreme, range of temperatures and pressures. There are 6.02×10^{23} particles of gas per mole, occupying 24l at normal temperature and pressure, which allows most of the assumptions to hold.

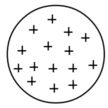
Questions

1. What does a scientist mean by a model?
2. Give two examples of well-known models in physics.
3. Give three observations about solids, liquids and gases which can be explained by the kinetic model.
4. What piece of evidence distinguished between the wave model and the particle model of light?
5. Give two pieces of evidence which support the Big Bang model of the origin of the universe.
6. Which experiment led to the adoption of the nuclear model of the atom?

Exam Workshop

This is a typical poor student's answer to an exam question. The comments explain what is wrong with the answers and how they can be improved. The examiner's mark scheme is given below.

(a) In the early 1900s, The accepted model of the atom was the "plum pudding model".



Electrons embedded in uniform positive charge

Geiger and Marsden scattered alpha particles off gold nuclei. Outline what the predictions of the plum pudding model would give. [2]

The alpha particles would be scattered. 0/2

The candidate has added nothing that was not in the question already. The candidate has failed to explain that "scattering" means deflected through small angles, randomly.

(b) Describe what results Geiger and Marsden actually obtained. [2]

Some particles were scattered at larger angles. 1/2

Some particles were indeed scattered through larger angles, but the candidate has failed to point out that most of the particles behaved as expected, nor outlined the significance of the few which did not behave as expected.

(c) Why could the plum pudding model not explain the results? [2]

The prediction did not fit. 0/2

The candidate has added nothing to previous answers

(d) Rutherford proposed the "nuclear" model of the atom. Describe the main features of the nuclear model. [2]

The nuclear model has a nucleus in the middle and electrons round it 1/2

The candidate understands at a superficial level, but has not demonstrated that s/he understands that all the positive charge and most of the mass is concentrated in a small region at the centre.

Examiner's Answers

(a) The alpha particles would be randomly deflected through small angles as they passed through the gold foil.

(b) Although most particles were deflected as expected, a small number were deflected through very large angles, even as much as 180^0.

(c) The large deflections could not be the result of several small ones in the same direction, because the gold was not thick enough to give that many deflections.

(d) The nuclear model had all the positive charge and most of the mass concentrated in a very small region at the centre of the atom.

Answers

1. A model is a set of ideas which can help our understanding of some aspects of reality.
2. Well-known models are the Kinetic theory model, the nuclear model of the atom, the Big Bang model of the origin of the universe, and the wave model of light.
3. The kinetic model satisfactorily predicts that solids keep their own shape, they expand on heating, they melt into liquids; liquids are almost incompressible, they evaporate into gases; gases are easily compressible, they spread out to fill any volume they are in; evaporation cools the remaining liquid and many more features.
4. The wave model requires light to travel slower in a denser medium, whereas the particle model predicts it must travel faster in order to explain the observed direction of refraction.
5. Two pieces of evidence which support the Big Bang model of the origin of the universe are the red shift of spectra from distance galaxies and the microwave background radiation.
6. The Rutherford scattering experimente led to the adoption of the nuclear model of the atom.

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