OXFORD CAMBRIDGE AND RSA EXAMINATIONS

Advanced GCE

PHYSICS B (ADVANCING PHYSICS) 2865/01

Advances in Physics

INSERT

Monday **26 JANUARY 2004** Morning 1 hour 30 minutes

INSTRUCTIONS TO CANDIDATES

- This insert contains the article required to answer the questions in Section A.

This insert consists of 8 printed pages.

The Physics of Cooking

Science in the kitchen

The kitchen offers many examples of physics, but a real understanding of the way in which physics is applied in the kitchen depends on a basic understanding of the nature of cooking.

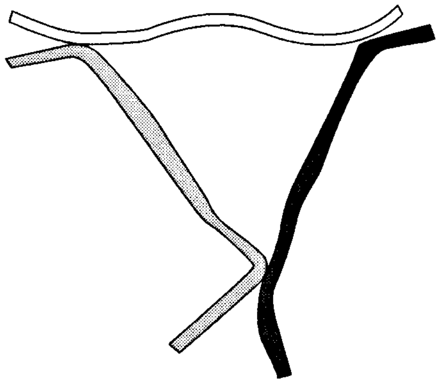
The chemistry of cooking can be very complex, but one simple idea is sufficient to explain much of it. The biological molecules found in meat, or in uncooked vegetables, are long-chain polymer molecules, which are often difficult or impossible for our digestive systems to break down. The cooking process splits up these polymer chains into forms that our digestive systems can deal with. At the same time, some of the small molecules produced carry the mouth-watering sensations of flavour to the flavour receptors in our noses. The important applications of physics in the kitchen – particularly heat transfer, and the microwave oven – are ways in which we can control and accelerate these processes.

The Chemistry of Cooking

The chemical and biological processes in many living things, such as mammals and birds, generally take place best at temperatures of about 37 °C (310 K), the temperature of our bodies. Although particularly hardy micro-organisms can survive in temperatures as low as 0 °C and as high as 115 °C, most living tissues are damaged at temperatures higher than about 40 °C. This is due to changes taking place in the protein molecules of the tissues.

The protein collagen is found in animal connective tissue, and it makes meat 'tough' to eat. This is because collagen consists of a triple helix of long-chain molecules, tightly wound together. At temperatures above about 70 °C the indigestible collagen molecules begin to disentangle to form gelatin, as shown in Fig. 1. The term 'tough' is used rather differently in describing strong materials such as metals.

collagen



gelatin

Fig. 1

Gelatin has fewer bonds between chains, which is why long, slow cooking makes meat tender and often causes it to it fall apart. For the same reason, gelatin is easily digested. Gelatin is used in jelly, where it forms open networks that hold water in large quantities. The presence of molecular pathways throughout the jelly means that it behaves as a solid, although heating to 30 °C weakens the links between the polymer chains, allowing the jelly to 'melt.'

More interesting processes take place at higher temperatures. In particular, chain-breaking reactions between proteins and carbohydrates occur at about 140 °C to produce a number of smaller molecules. These reactions are called Maillard reactions. The activation energy for a Maillard reaction – typically about 70 kJ mol^{-1} (about 1.2×10^{-19} J or 0.7 eV per molecule) – is two or three times higher than the energy needed to disentangle protein chains, as stronger bonds need to be broken. Some of these small molecules are responsible for the characteristic appetising smell of cooking, while others produce the brown colours of cooked food.

To speed up cooking, you can heat the food to a higher temperature. The rate of a chemical reaction with activation energy E depends on the Boltzmann factor $f_B = e^{-\frac{E}{kT}}$. At typical cooking temperatures, every 10 K rise in temperature T roughly doubles the rate of the reactions concerned, and cooks the food faster. On the negative side, at higher temperatures, Maillard reactions produce bitter flavours as well as chemicals which it has been suggested could contribute to cancer of the digestive system. Furthermore, if the temperature of the food is raised too much, the molecules are broken down completely to leave brown residues of carbon. This is caramelisation, which is fine in crème caramel or in gravy browning, but is not usually wanted when cooking – just think of badly-barbecued sausages, raw in the middle and thick sooty carbon on the outside!

Kitchen Thermometers

Whether food is cooked or not depends on its temperature, so a thermometer is an obvious scientific instrument to bring to the kitchen. If nothing else, you can check the temperature settings of your oven, to see how accurate they are! Liquid-in-glass jam thermometers have been common for many years, but electronic thermometers are now readily available. These allow the temperature at the very centre of the food, such as a piece of meat, to be measured during cooking. The sensor of the electronic thermometer, either a thermistor or a thermocouple, is stuck deep into the piece of meat and a cable connects it to an electronic circuit and digital display unit.

Conduction of Heat

Recipes normally give oven settings and approximate cooking times based on the mass of the food being cooked, but these do not allow for the different thickness of different shapes. The two cakes of Fig. 2 have the same mass, but different shapes.

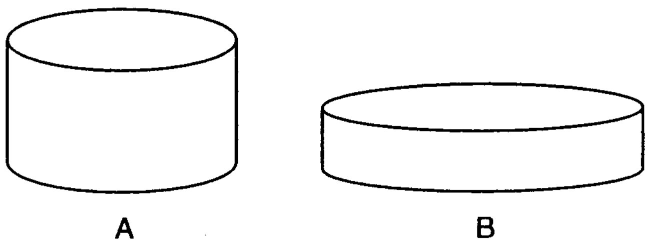


Fig. 2

If these are baked for the same time, either cake A will be uncooked in the centre or cake B will be overdone. Cake A cooks more slowly because its centre is a greater distance from the surface than the centre of B is. To understand the conduction of heat, it is useful to model it on a more familiar conduction process: the conduction of electricity.

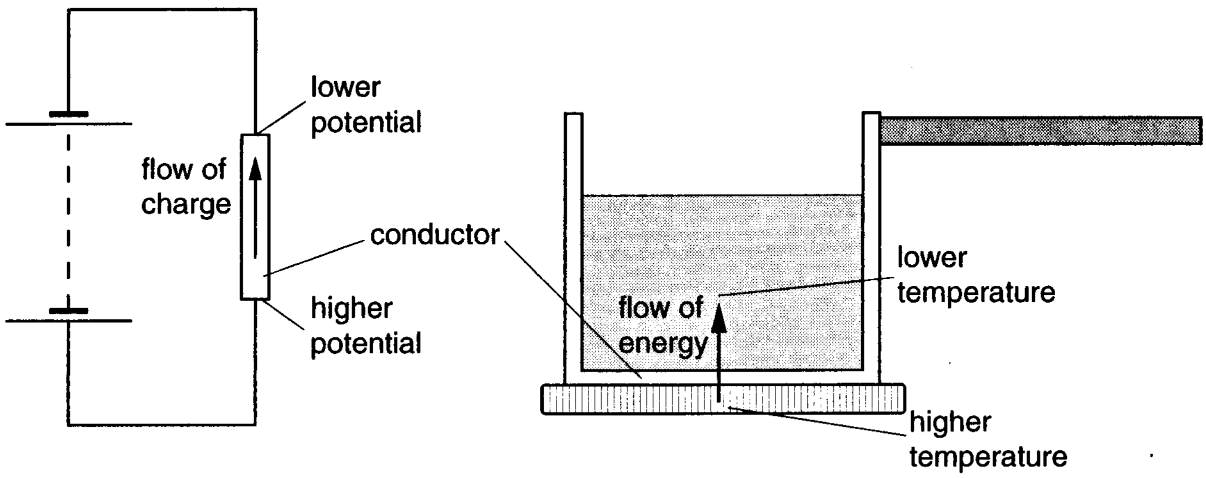


Fig. 3

	electrical conduction	thermal conduction
What is conducted?	electrical charge	heat
What is the rate of flow?	current, I (charge per second)	power transfer, P (energy per second)
What causes the flow?	potential difference, V	temperature difference, ΔT
What relates the flow to its cause?	electrical conductance, G	thermal conductance, G_T
How are these quantities related?	$I = GV$	$P = G_T \Delta T$

In an electrical circuit, a potential difference V across an electrical conductor of conductance G causes a flow of charge in it, producing a current $I = GV$. In the case of conduction of heat, a temperature difference ΔT across a thermal conductor of thermal conductance G_T, such as the base of the saucepan in Fig. 3, causes energy to flow through it at a rate $P = G_T \Delta T$. For an electrical conductor, there are three ways to increase its conductance — increase its cross-sectional area A, decrease its length L, or use a material of higher electrical conductivity σ. Each of these changes would give a greater current I for the same potential difference V. In the same way, the flow of heat through the base of a saucepan (Fig. 3) can be increased by increasing the area of the base, decreasing its thickness or using a material such as copper which has a high thermal conductivity.

If you apply this model to the cakes in Fig. 2, you can see that the distance L between the hot oven outside the cake and the cooler centre of the cake is smaller for cake B, so its thermal conductance is greater. Heat energy will be conducted into the centre of cake B more rapidly, so that the internal temperature of cake B will rise more rapidly, and it will cook more rapidly.

Absorbing radiant energy

Frying transfers energy into food by conduction, and convection is the method of energy transfer in ovens. In grills and barbecues, the food absorbs infrared photons radiated by a glowing heat source. These photons are readily absorbed in the outer layers of the food and rapidly raise its temperature enough to cause Maillard reactions and, if you are not careful, to decompose it into carbon.

Photons of much lower energy have also been used to cook and reheat food since the end of the Second World War, when radar engineer Percy Spencer noticed a chocolate bar in his pocket became soft while he was standing near a magnetron used for generating microwaves. Since that time, microwave ovens have been increasingly common in kitchens, although many people do have misconceptions about them.

Generating microwaves

Microwave ovens generate their microwaves in **magnetrons** similar to those used in early radar apparatus. The construction of a magnetron is shown in Fig. 4.

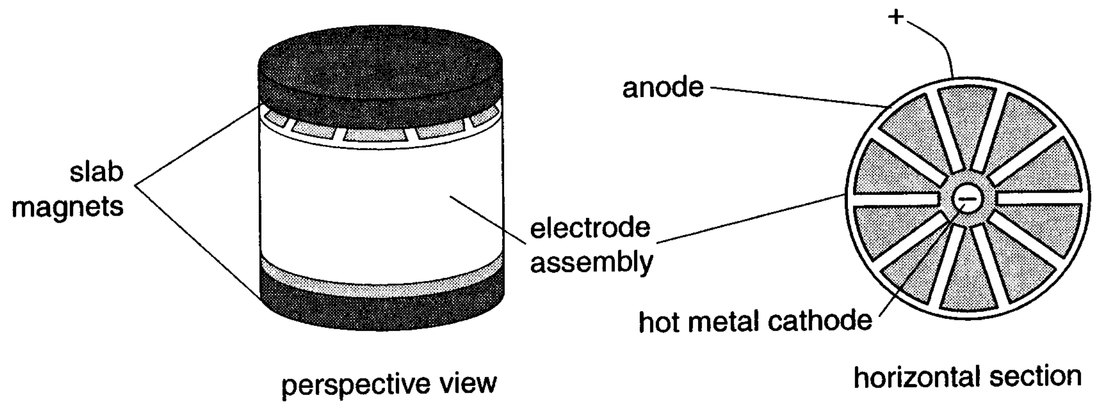


Fig. 4

A strong vertical magnetic field between the permanent magnets, together with a radial electrical field between the central cathode and the surrounding hollow anode, make the electrons emitted by the hot cathode travel in spiral paths. This is shown in Fig. 5.

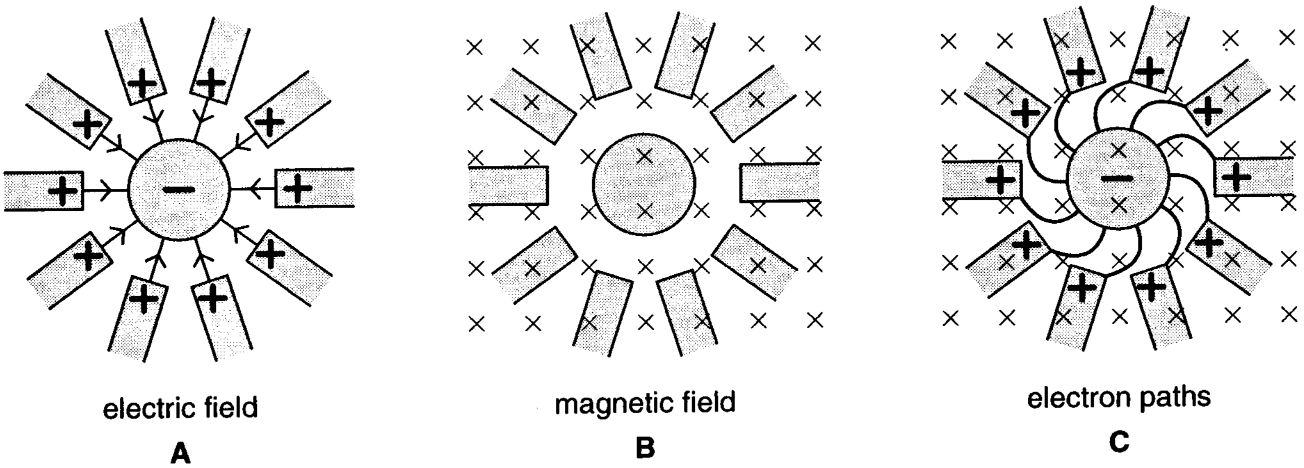
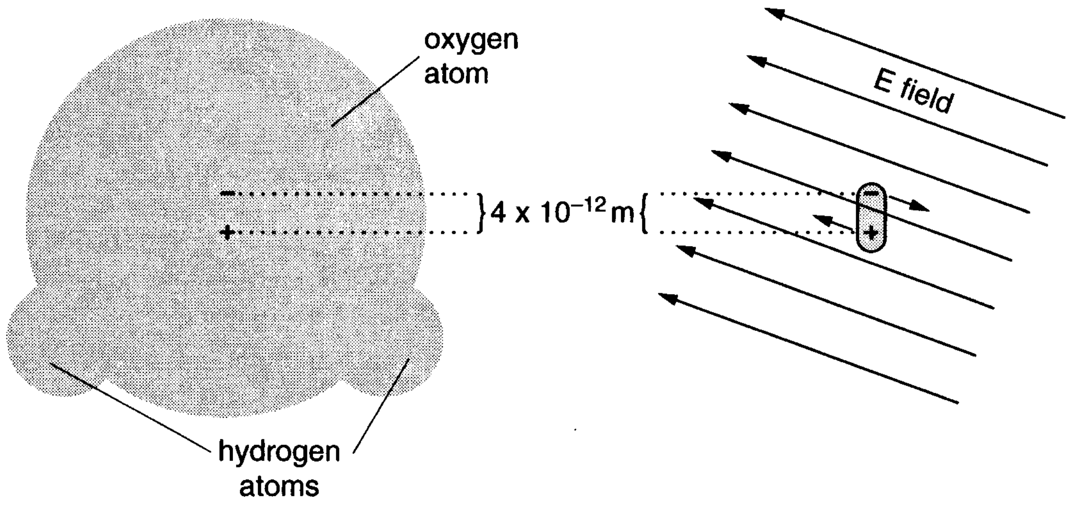


Fig. 5

While the electrons are pulled up the electric field lines of Fig. 5 A, they are pushed at right angles by the magnetic field shown in Fig. 5 B, vertically down into the diagram. As a result of the combination of these two forces, electrons travel in the spiral paths shown in Fig. 5 C. The physical structure of the hollow anode makes the spiralling cloud of electrons become turbulent, and the fluctuations cause oscillating electrical currents in the different parts of the hollow anode. The resonance here is similar to the sound produced by blowing over the top of a bottle or pen-top: turbulence near the rim produces standing waves. In a typical magnetron used in a microwave oven, the standing waves have a resonant frequency of 2.45 GHz. An aerial connection to part of the hollow anode carries the electrical oscillations to a wave-guide, where the resulting microwaves are 'piped' into the oven.

Using microwaves to heat food

Infrared photons have been associated with heating since William Herschel first observed an invisible portion of the spectrum heating up a thermometer. A typical infrared photon has an energy of 0.1 eV to 1.0 eV. This is readily absorbed by molecular bonds, as you can see when you toast bread or grill fish. But why do microwave photons, with energies about 10^4 times smaller, also heat materials? To understand this, you need to consider the shape and nature of a water molecule. As Fig. 6 A below shows, a water molecule is asymmetrical.



A B

Fig. 6

The electrons within the molecule are also asymmetrically distributed in the molecule, being closer on average to the oxygen atom than to the two hydrogen atoms. This means that the centre of charge of the ten protons in the molecule and the centre of charge of the ten electrons are not at the same place, but separated by about 4×10^{-12} m, or about one-tenth of the diameter of the molecule. This separation of charges means that a water molecule is a dipole, and behaves in an electric field in much the same way as a bar magnet in a magnetic field. This is shown in Fig. 6 B, where the two charges of the dipole are pushed in opposite directions by the applied electric field.

The water molecules oscillate in the alternating electric field of the microwaves. As individual molecules oscillate, the work done against the forces between neighbouring molecules increases their kinetic energy in a random way, raising the temperature.

Resonance in the microwave oven

The absorption of microwaves by water molecules is often described as resonance, but this is not true: free water molecules resonate at 22 GHz and 183 GHz. Microwaves with a frequency of 22 GHz would be totally absorbed in the surface of the food without penetrating. If waves with a frequency as low as 100 MHz were used, they would pass straight through the food, and it would not heat up. The choice of 2.45 GHz is a compromise. At 2.45 GHz, the microwaves penetrate about 1 cm into the food, which is contrary to the common misconception that 'microwaves heat food from the middle out!'

One place other than the magnetron where resonance is found in a microwave oven is in the box-like cavity of the oven itself. The metal oven walls reflect the microwaves repeatedly inside the cavity, and superposition of the reflected waves produces regions where the intensity is a maximum and regions where it is a minimum, like the nodes and antinodes of sound waves in a pipe. With a typical microwave oven measuring 3 x 3 x 2 wavelengths, the whole cavity will resonate with a particular pattern of nodes and antinodes. As a consequence, some points will have very low microwave intensity and will not cook effectively. To combat this, the standing wave pattern is moved relative to the food, either by rotating the food on a turntable or by reflecting the microwaves off a rotating 'stirrer' as they enter the oven. The food should also be turned or stirred at intervals, and allowed to rest after cooking to give time for conduction of heat within the food.

Copyright Acknowledgements:

Thanks to Dr Peter Barham, University of Bristol, for permission to use material from his book *The Science of Cooking* (Springer-Verlag 2001)