RECOGNISING ACHIEVEMENT

SPECIMEN

Advanced GCE

PHYSICS B (ADVANCING PHYSICS)

G495 QP

Unit G495: Field and Particle Pictures

Specimen Paper

Candidates answer on the question paper.

Additional Materials:
Electronic calculator
Data, Formulae and Relationships booklet

Time: 2 hours

Candidate Name

Centre Number

Candidate Number

INSTRUCTIONS TO CANDIDATES

- Write your name, Centre number and Candidate number in the boxes above.
- Answer **all** the questions.
- Use blue or black ink. Pencil may be used for graphs and diagrams only.
- Read each question carefully and make sure you know what you have to do before starting your answer.
- Do **not** write in the bar code.
- Do **not** write outside the box bordering each page.
- WRITE YOUR ANSWER TO EACH QUESTION IN THE SPACE PROVIDED.

INFORMATION FOR CANDIDATES

- The number of marks is given in brackets [] at the end of each question or part question.
- ✎ Where you see this icon you will be awarded marks for the quality of written communication in your answer.
- You may use a calculator.
- You are advised to show all the steps in any calculations.
- The total number of marks for this paper is **100**.

FOR EXAMINER'S USE		
Section	**Max.**	**Mark**
A	**19**	
B	**43**	
C	**38**	
TOTAL	**100**	

This document consists of **29** printed pages and **3** blank pages and an Insert.

[Turn Over

Answer **all** the questions.

Section A

1 Protons and neutrons are each made up of a different combination of three quarks.

The u quark has a charge of $+\frac{2}{3}$e. The u quark has a charge of $-\frac{1}{3}$e.

State the combination of three quarks needed to make

(a) a proton

.... **[1]**

(b) a neutron.

.... **[1]**

2 A nucleus of hydrogen-3 can be formed when a neutron is absorbed by a nucleus of hydrogen-2.

$${}^{2}_{1}\text{H} + {}^{1}_{0}\text{n} \rightarrow {}^{3}_{1}\text{H}$$

The table gives the masses of the three particles in atomic mass units (u).

particle	mass/ u
${}^{1}_{0}\text{n}$	1.008 67
${}^{2}_{1}\text{H}$	2.001 41
${}^{3}_{1}\text{H}$	3.001 60

Show that about 1×10^{-12} J of energy is released for each nucleus of hydrogen-3 created in this way.

u = 1.7×10^{-27} kg

$c = 3.0 \times 10^{8}$ m s^{-1}

[3]

3 A mercury discharge lamp emits ultraviolet photons of frequency 1.2×10^{15} Hz.

(a) Show that the energy of the ultraviolet photons is about 8×10^{-19} J.

$h = 6.6 \times 10^{-34}$ J s

[1]

(b) Fig. 3.1 gives some of the energy levels of the mercury atom.

Draw an arrow to show the energy level transition which causes the emission of these ultraviolet photons.

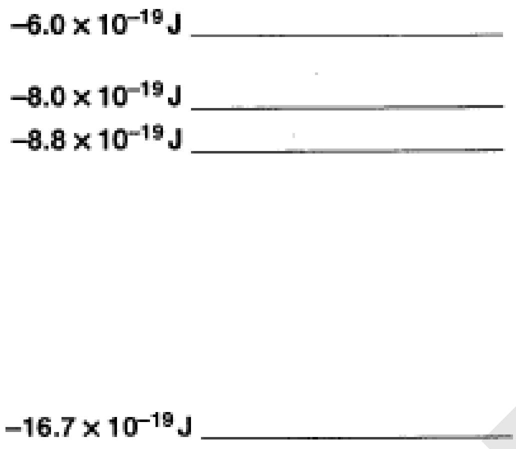

Fig. 3.1

[1]

(c) Here are some statements (**A**, **B** and **C**) about the energy levels shown in Fig. 3.1.

A They are all negative because the electrons in the atom are bound to the nucleus.

B They are all negative because electrons have a negative charge.

C Electrons in different energy levels have the same de Broglie wavelength.

Which **one** of these statements is correct?

answer .... **[1]**

4 The surface of an isolated conducting sphere is at a negative potential of -160 kV,

The radius of the sphere is 0.1 m.

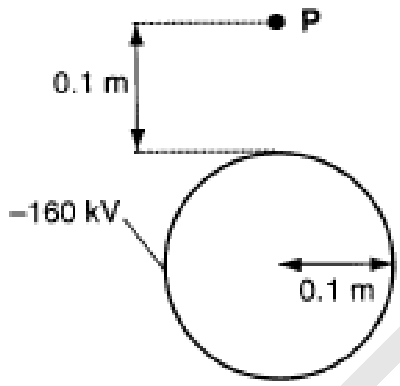

Fig. 4.1

(a) Draw an arrow through point **P** to show the direction of the electric field at that point.

[1]

(b) Here is a list of potentials.

-320 kV **-160 kV** **-80 kV** **-40 kV**

P is at a distance of 0.1 m from the surface of the sphere.

State which is the best value for the potential at **P**.

potential = ...kV **[1]**

(c) Draw a line on Fig. 4.1 to show the shape of the equipotential which passes through point **P**.

[2]

5 Fig. 5.1 shows a single coil of wire in the uniform field between opposite poles of a pair of magnets.

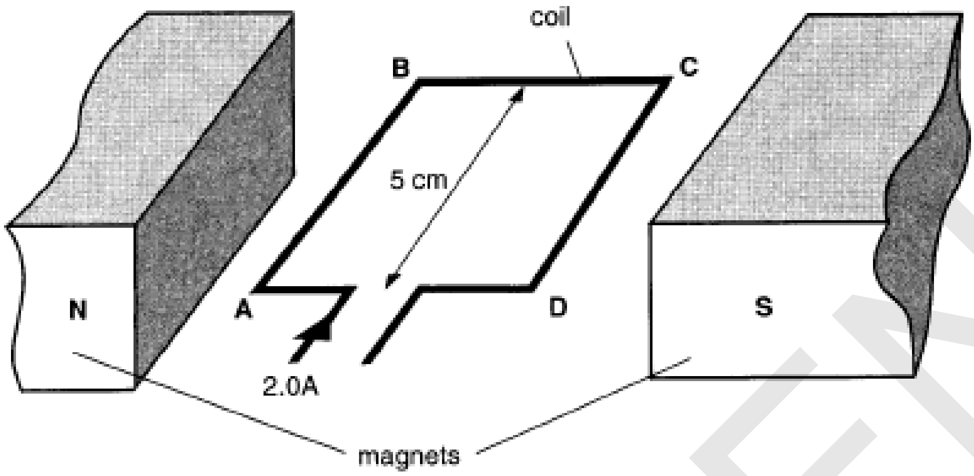

Fig. 5.1

The average flux density between the poles is 25 mT.

(a) Calculate the vertical magnetic force on side **AB** when it carries a current of 2.0 A.

The length of side **AB** is 5.0 cm.

force = ... N **[2]**

(b) Here are three statements about the magnetic force on side **BC** when the coil carries a current.

A It has the same value and direction as the force on side **AB**.

B It has the same value but the opposite direction to the force on side **AB**.

C There is no magnetic force on side **BC**.

State which **one** of the three (**A**, **B** or **C**) is correct.

answer .... **[1]**

6 The graph of Fig. 6.1 shows the variation of binding energy per nucleon with the total number of nucleons in a nucleus.

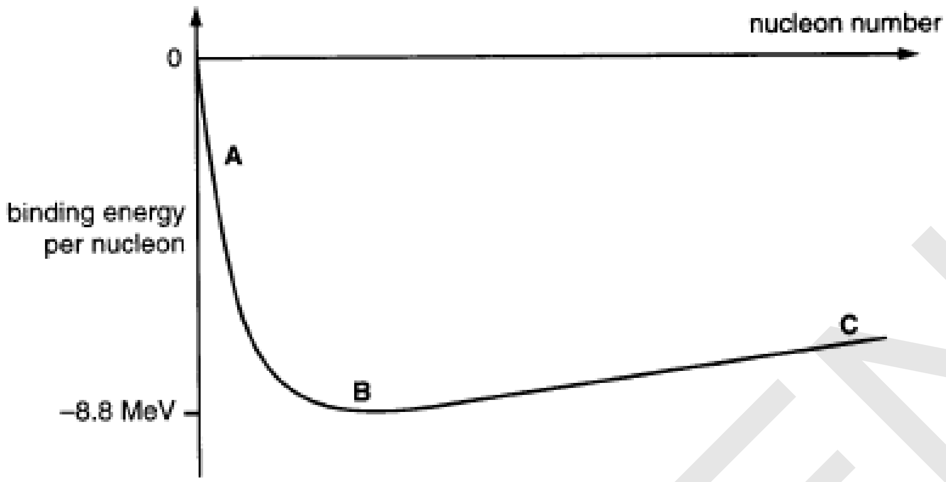

Fig. 6.1

Three regions (**A**, **B** and **C**) are marked on the graph.

State the region (**A**, **B** or **C**) which

(a) contains the nucleon number 56

.... **[1]**

(b) contains nuclei which can be used to provide energy by nuclear fusion

.... **[1]**

(c) contains nuclei which undergo nuclear fission.

.... **[1]**

7 The graph of Fig. 7.1 shows the variation of **electric field strength *E*** with **distance *r*** from a charged particle.

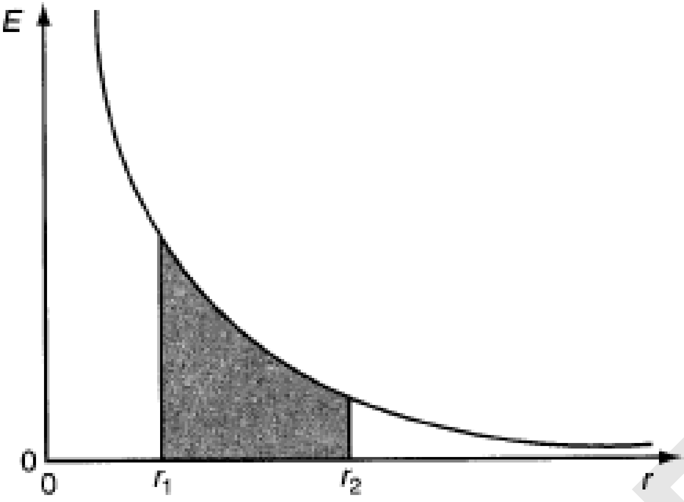

Fig. 7.1

Here are some statements about the shaded area shown on the graph.

A The area gives the average electric force between points r_1 and r_2.

B The area gives the work needed to move an electron from r_1 to r_2.

C The area gives the potential difference between points r_1 and r_2.

State which **one** of the three (**A**, **B** or **C**) is correct.

answer .... **[1]**

[Section A Total: 19]

Section B

8 This question is about the changing magnetic fields in transformers.

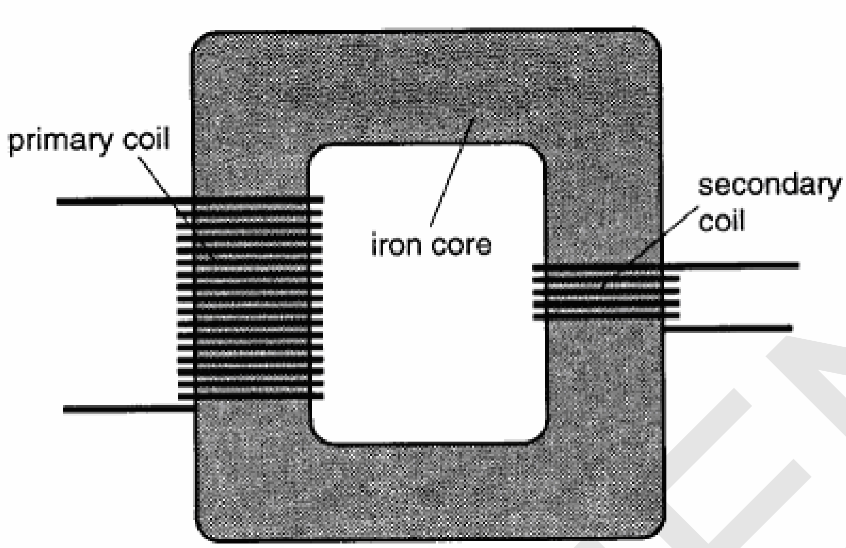

Fig. 8.1

An iron core is wound with primary and secondary coils of insulated copper wire to make a transformer, as shown in Fig. 8.1.

(a) On Fig. 8.1, sketch **two** complete loops of magnetic flux which pass through the secondary coil when there is a current in the primary coil.

[2]

(b) The ends of the secondary coil are connected to an oscilloscope to obtain the emf-time graph of Fig. 8.2

On the axes of Fig. 8.2, sketch the variation with time of the magnetic flux in the secondary coil.

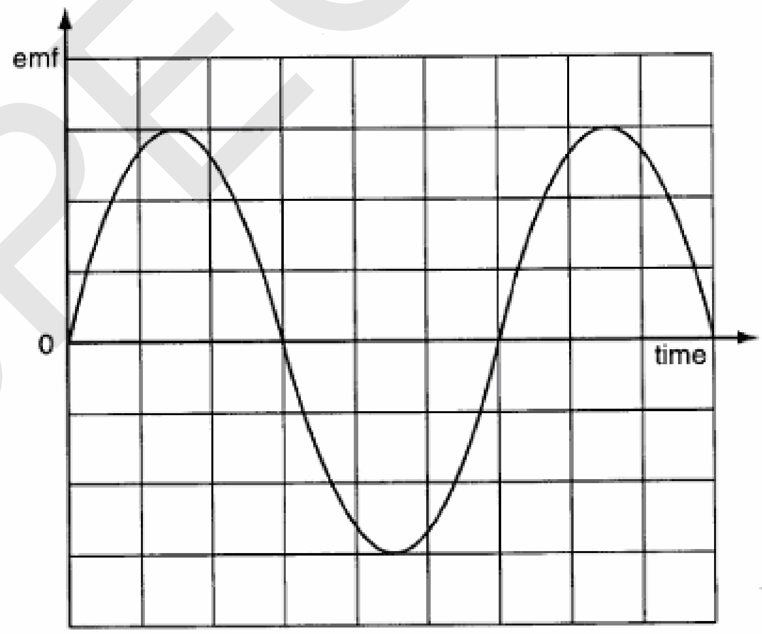

Fig. 8.2 **[2]**

(c) For an ideal transformer, the magnetic flux in the secondary coil is the same as the magnetic flux in the primary coil.

Use this to explain why the quantity $\frac{\text{emf across the coil}}{\text{turns of wire in the coil}}$

Has the same value for both primary and secondary coils in an ideal transformer.

[2]

(d) In a real transformer, eddy currents in the iron core will alter the flux in the two coils.

Explain why eddy currents are set up in the core and suggest why this alters the flux in the core.

✎ *You will be awarded marks for the quality of your written communication.*

[4]

[Total: 10]

Turn Over

9 This question is about triggering the rapid release of gamma rays from a nucleus.

Fig. 9.1 shows some of the energy levels for a nucleus of hafnium-178.

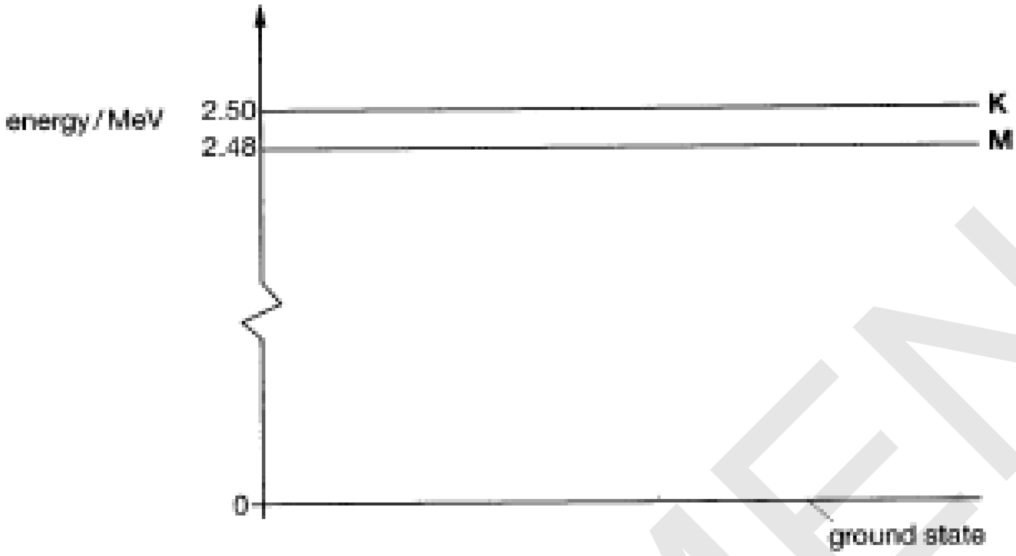

Fig. 9.1

(a) Halfium-178 is created by bombarding a target of tantalum-181 with high energy protons from an accelerator. The process is represented by the equation below.

$$^{181}_{73}\text{Ta} + {}^{1}_{1}\text{p} \rightarrow {}^{178}_{72}\text{Hf} + \text{X}$$

Calculate the nucleon number and proton number of particle X, and hence identify it.

[1]

(b) Some of the hafnium-178 nuclei created are in the excited state labelled **M** in Fig. 9.1. Nuclei in state **M** decay very slowly, with a decay constant of 7.1×10^{-10} s^{-1}.

In a recent experiment, a sample of 5.0 ng of hafnium-178 was created in state **M**.

Calculate the **activity** of the sample. Include the unit of your answer.

$1\ u = 1.7 \times 10^{-27}$ kg

activity = ... unit .... **[5]**

(c) The sample of hafnium-178 in state **M** was exposed to a one second pulse of X-ray photons of wavelength 6.2×10^{-11} m.

(i) Calculate the energy of each X-ray photon in MeV.

$c = 3.0 \times 10^{8}$ m s^{-1}

$h = 6.6 \times 10^{-34}$ J s

$e = 1.6 \times 10^{-19}$ C

photon energy = ... MeV [3]

(ii) The X-ray photons are absorbed by the sample, raising some nuclei to the energy level **K**. These nuclei have a larger decay constant than those in level **M**.

State and explain what will happen to the activity of the sample of hafnium. .

[3]

[Total: 12]

10 This question is about accelerating particles to high energies.

Particles are accelerated in a ring-shaped evacuated tube as shown in Fig. 10.1.

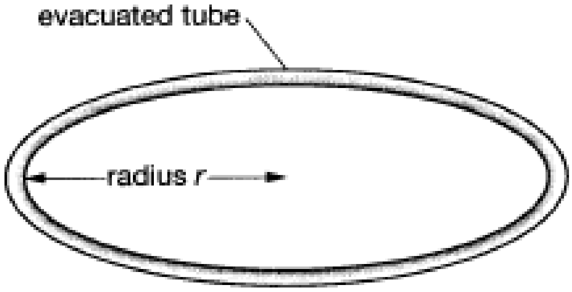

Fig. 10.1

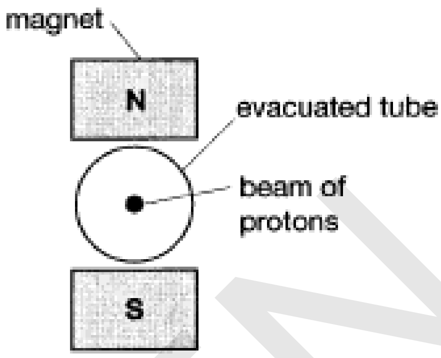

Fig. 10.2

(a) A particle accelerator of this type at CERN accelerates protons to a total energy of 270 GeV.

Use the relationship $E_{rest} = mc^2$ to show that the energy 270 GeV is about 300 times the rest energy of the protons.

$m_p = 1.7 \times 10^{-27}$ kg

$e = 1.6 \times 10^{-19}$ C

$c = 3.0 \times 10^8$ m s^{-1}

[3]

(b) Fig.10.2 shows the magnets above and below the evacuated tube. These force protons moving along the tube to follow a circular path.

(i) Low energy protons of mass *m* and charge *q* move at speed *v* through the magnetic field of flux density *B*. By using the expressions for the centripetal force and magnetic force on the protons, show that the radius *r* of the circular path is given by the expression

$$r = \frac{mv}{Bq}.$$

[2]

(ii) Protons with a large total energy *E* move at almost the speed of light *c*.

In these conditions, the radius *r* of the circular path is given by the expression $B = \frac{E}{cqr}$

Calculate the magnetic flux density required to keep the 270 GeV protons in a circular path of radius 1.8×10^3 m.

$c = 3.0 \times 10^8 \text{ m s}^{-1}$

$e = 1.6 \times 10^{-19}$ C

flux density = ...T **[2]**

(c) In an experiment, protons and antiprotons travel in opposite directions through the evacuated tube.

(i) Suggest why protons and antiprotons travel in opposite directions through the evacuated tube.

[1]

(ii) Sometimes, when a proton and an antiproton collide, a particle called the **Z** is created.

The Z particle is unstable and decays quickly into a positron and an electron.

Complete the equation for the decay of the Z particle, showing nucleon and charge numbers.

$$^{0}_{0}Z \rightarrow$$

[2]

(iii) The experiment shows that the Z particle has a rest energy of 93 GeV.

Suggest how this is determined by the experiment.

[1]

[Total: 11]

11 This question is about calculating the risk to workers exposed to radioactive materials.

Disposable surgical instruments are sterilised by gamma photons from a sample of cobalt-60. The instruments in their airtight plastic bags are packed into boxes and placed on the conveyor belt, as shown in Fig.11.1.

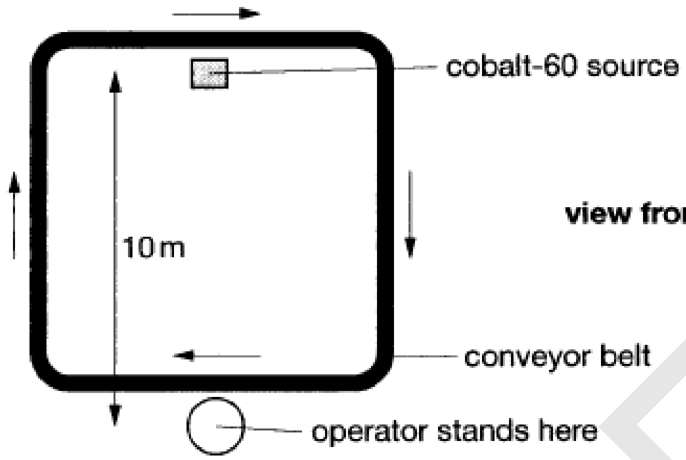

Fig. 11.1

(a) Operators are required to stand on a spot that is 10 m from the cobalt-60 source. Boxes that they load onto the conveyor belt pass much closer to the cobalt-60, and are exposed to a high intensity of gamma photons. The intensity I of gamma photons at a distance d from a source which emits photons at a rate A is given by the expression

$$I = \frac{A}{4\pi d^2}$$

(i) The source emits gamma photons at a rate of 2.4×10^{16} Bq.

Show that the intensity of gamma photons for the operators would be about 2×10^{13} Bq m^{-2} in the absence of shielding.

[1]

(ii) Explain why the intensity of gamma photons decreases with increasing distance from the source.

[2]

(iii) A nucleus of cobalt-60 releases a beta particle when it decays, quickly followed by a pair of gamma photons.

Explain why the beta particles contribute very little to the absorbed dose of the operator.

[1]

(b) In order to reduce the intensity of gamma photons for the operators to a safe level, a 1.2 m thick wall of concrete is placed between them and the source, as shown in Fig. 11.2.

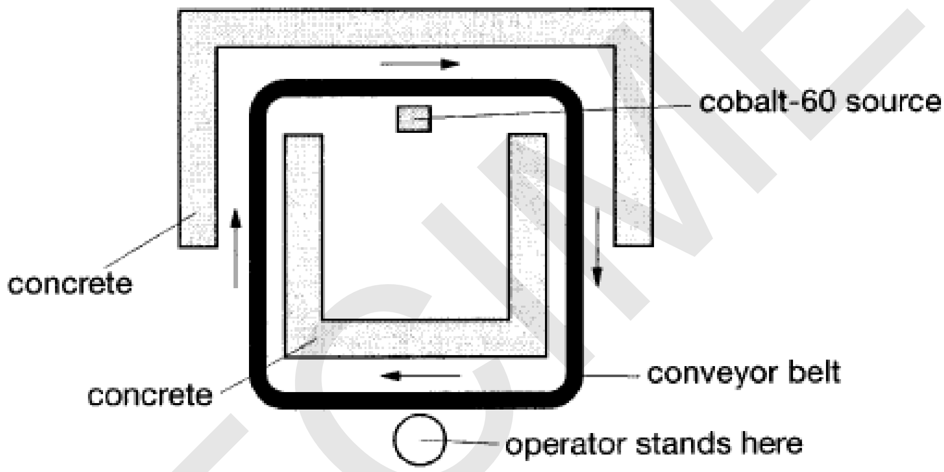

Fig. 11.2

(i) The intensity of the photons is halved for each 4.0×10^{-2} m thickness of concrete that they pass through.

Show that the 1.2 m thickness of concrete reduces the intensity of gamma photons for the operator to about 2×10^{4} Bq m^{-2}.

[2]

[Turn Over

(ii) Each operator presents an average area of 0.80 m^2 for absorption of the gamma photons.

If all the photons are absorbed by an operator of mass 75 kg, show that the absorbed dose of the operator is below the recommended safe limit of 4.0×10^{-6} Sv per day.

energy of photons = 1.8×10^{-13} J

quality factor of gamma photons = 1

[4]

[Total: 10]

[Section B total: 43]

Section C

The questions in this section are based on the Advance Notice article.

12 This question is about the energy and momentum of 5.4 MeV alpha particles (lines 9–13 in the article).

(a) 5.4 MeV alpha particles have an energy of 8.6×10^{-13} J.

Show that they are travelling at a speed of about 2×10^{7} m s^{-1}.

mass of alpha particle = 6.6×10^{-27} kg

[2]

(b) Fig. 12.1 shows an alpha particle being emitted at 2×10^{7} m s^{-1} from a nucleus of ${}^{210}_{84}Po$.

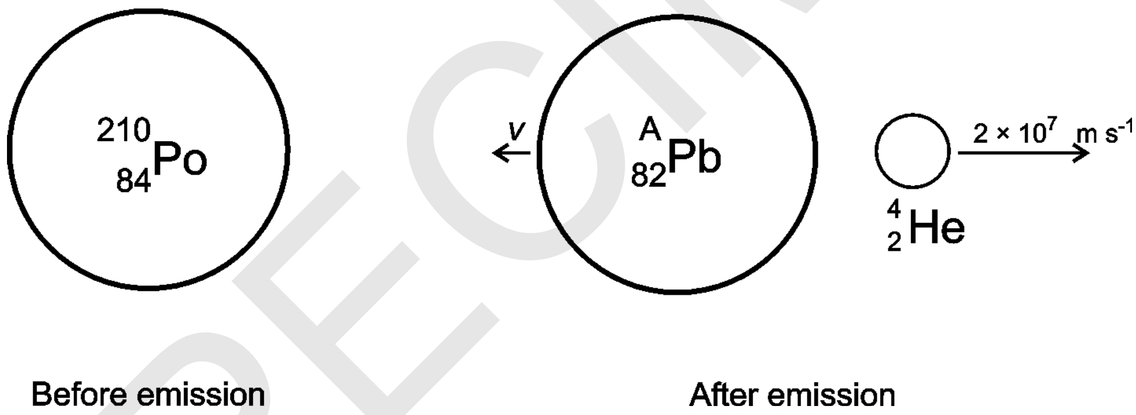

Fig. 12.1

(i) Write down the mass number A of the lead (Pb) nucleus produced in the decay.

mass number = ... **[1]**

(ii) Show that the lead nucleus in Fig. 12.1 is recoiling at a speed v of about 3×10^5 m s^{-1}.

[2]

(iii) Explain why the article is justified in stating (line 12 in the article) that nearly all the energy is given to the alpha particle.

.

[2]

[Total: 7]

13 This question is about the changes during beta decay (lines 16–24 in the article).

An example of beta decay is the decay of bismuth-210 to polonIum-210.

$$^{210}_{83}\mathrm{Bi} \rightarrow \, ^{210}_{84}\mathrm{Po} + \, ^{0}_{-1}\mathrm{e} + \bar{\nu}$$

(a) How does this equation show that the anti-neutrino $\bar{\nu}$ is uncharged?

[1]

(b) Explain why uncharged particles such as neutrons or neutrinos are harder to detect than charged particles such as alpha or beta particles.

[1]

(c) **(i)** Suggest reasons why most physicists were reluctant to abandon the principle of conservation of energy in nuclear reactions, as Niels Bohr had suggested (lines 26-27 in the article).

✐ *You will be awarded marks for the quality of your written communication*

(ii) Suggest reasons why Pauli's suggestion of an extremely tiny, uncharged particle (lines 27 – 31 in the article) was not immediately accepted.

[6]

[Total: 8]

14 This question is about the detection of neutrinos.

In Reines & Cowan's experiment (lines 40 –70 in the article), the positron created in the reaction $\bar{\nu} + {}^{1}_{1}\text{p} \rightarrow {}^{1}_{0}\text{n} + {}^{0}_{+1}\text{e}$ annihilates with an electron to produce a pair of gamma photons as shown in Fig. 14.1.

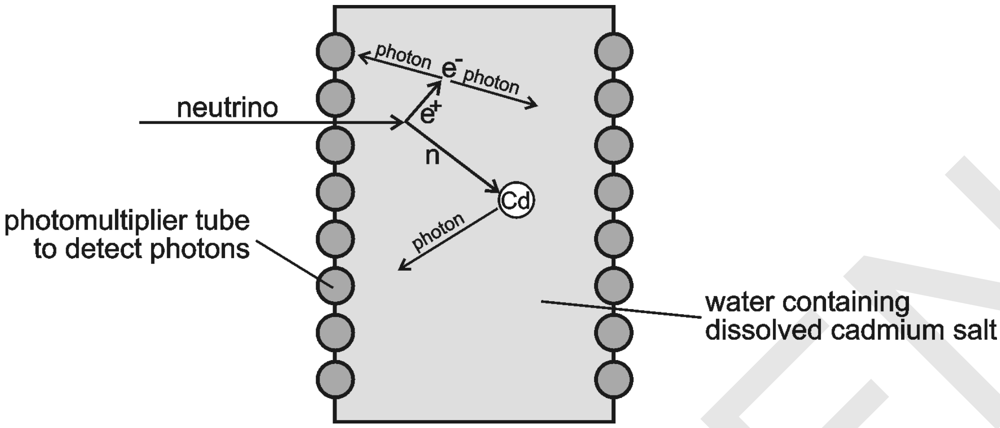

Fig. 14.1

(a) Explain why the detector uses **two** banks of photomultiplier tubes to detect the photons produced by the positron annihilation.

[1]

(b) Reines and Cowan made their measurements over nearly a fortnight, and repeated the experiment over two days with the reactor off. Fig. 14.2 shows the results they obtained, where each 'count' consists of the pair of photons of part (a) followed by the later photon of part (b).

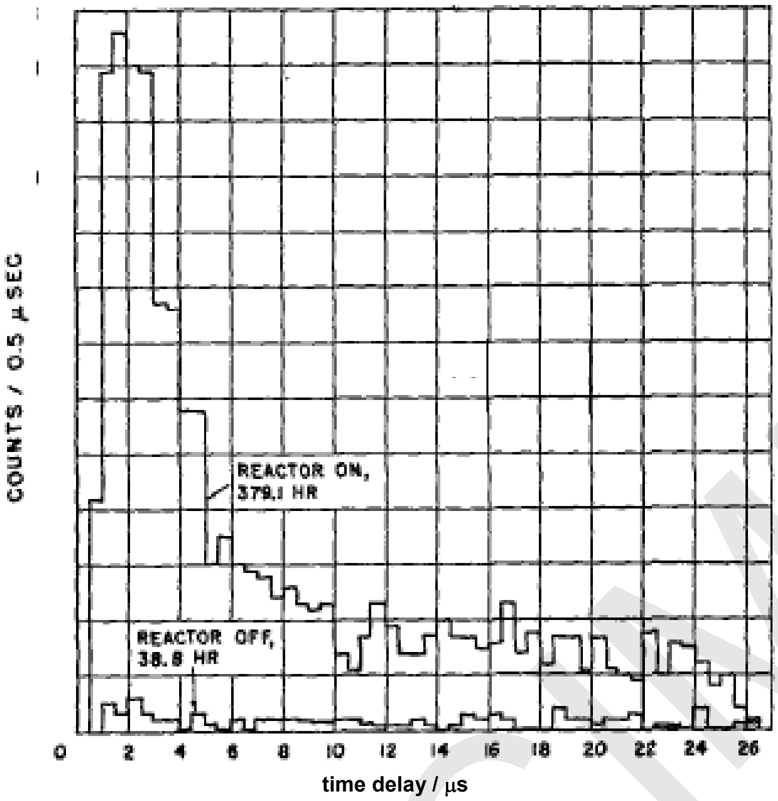

Fig. 14.2

(i) Explain why values on the lower, 'noise' graph need to be multiplied by about 10 for proper comparison with the upper, 'signal' graph.

[1]

(ii) Explain clearly how the results show that Reines and Cowan had shown the presence of neutrinos despite the signal to noise problem described in the article (lines 57 - 70 in the article).

[3]

(c) Reines and Cowan performed their experiments in nuclear reactors in Hanford and in Savannah River.

(i) Describe how scientific understanding of neutrinos benefited from the American nuclear weapons programme in the 1950s.

[2]

(ii) Suggest reasons why a government proposal to build a facility with both military and pure science objectives would be controversial today.

[2]

[Total: 9]

[Turn Over

15 This question is about the Homestake neutrino detector (lines 82–96 in the article).

(a) Argon-37 atoms were created in the Homestake neutrino detector at a steady rate of about 12 per month for many years. The decay constant of argon-37 is $2.3 \times 10^{-7}\ s^{-1}$.

Show that the half life of argon-37 is about a month (2.6×10^{6} s).

[1]

(b) Suggest difficulties that Ray Davis will have met in measuring the count rate of decaying argon-37 atoms in the Homestake detector (lines 82 –88 in the article).

✎ *You will be awarded marks for the quality of your written communication.*

[4]

[Total: 5]

16 **(a)** This question is about movement of photons and neutrinos in the Sun's core (lines 98– 114 and Fig. 5 in the article).

Show that a photon travels a total distance of about 4×10^{20} m in 40 000 years.

$c = 3.0 \times 10^{8}$ m s^{-1}, 1 year = 3.2×10^{7} s

[2]

(b) By comparison with diffusion of gas molecules (lines 105 – 114 and Fig. 4 in the article), it is believed that photons travel about 4 × 1020 m to the Sun's surface.

Explain why solar neutrinos may arrive at the Earth 40 000 years sooner than photons produced as a consequence of the same fusion reactions. No calculations are necessary.

[2]

(c) Measurements of solar neutrinos detected at the Earth give results about one-third of those expected. Physicists were concerned about this large difference (lines 87 – 96 in the article).

Suggest and explain reasons for their concern.

Your answer should make reference to

- the accepted model of energy production in the Sun (lines 98 – 99 in the article)
- possible sources of uncertainty in the experiments
- the consequence of a real difference between the current rate of solar energy production and that inferred from reactions 40 000 years ago.

[5]

[Total: 9]

[Section C Total: 38]

[Paper Total: 100]

Advanced GCE

PHYSICS B (ADVANCING PHYSICS)

G495

Unit G495: Field and Particle Pictures
Advance Notice Article

Specimen

May be opened and given to candidates upon receipt.

INSTRUCTIONS TO CANDIDATES

- Take the article away and read it carefully. Spend some time looking up any technical terms or phrases you do not understand. You are not required to research further the particular topic described in the article.
- For the examination on ……. you will be given a fresh copy of this Advance Notice article, together with a question paper. You will not be able to take your original copy into the examination with you.
- The value of standard physical constants will be given in the Advancing Physics Data, Formulae and Relationships booklet. Any additional data required are given in the appropriate question.

INFORMATION FOR CANDIDATES

- Questions in Section C of Paper G495, Field and Particle Pictures, will refer to material in this Advance Notice.
- Section C will be worth about 40 marks.
- Sections A and B will not be based on the material in the Advance Notice.

This document consists of **6** printed pages and **2** blank pages.

Neutrinos: detecting the undetectable

Problems with beta decay

In the early years of the twentieth century, Ernest Rutherford showed that alpha particles are helium nuclei and beta particles are electrons. Physicists soon realised that fairly simple changes were taking place in the nuclei of alpha- and beta-emitters, but there were serious problems with the physics in beta-particle emission. The speed, and therefore the kinetic energy, of the emitted charged particles can be found by measuring the curvature of the paths they form in magnetic fields, although rather strong magnetic fields are needed in the case of alpha particles.

When the kinetic energy of alpha particles emitted by polonium-210 is measured, the spectrum of Fig. 1 is obtained. This is exactly what would be expected: each decay liberates the same amount of energy, and conservation of momentum allows only one way for the sharing of this energy. Nearly all the energy is given to the alpha particles, which all emerge with the same energy of 5.4 MeV.

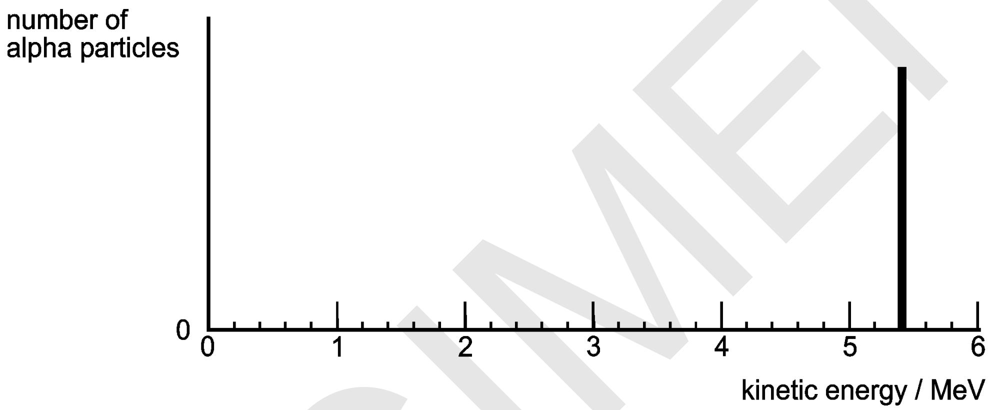

Fig. 1

In beta decay, electrons emerge from the nuclei at higher speeds than the alpha particles produced by alpha decay, but with rather less kinetic energy. Physicists thought that these electrons should all have exactly the same energy as each other, but Fig. 2 shows the beta particle energy spectrum obtained when nuclei of bismuth-210 decay. The energy varies greatly.

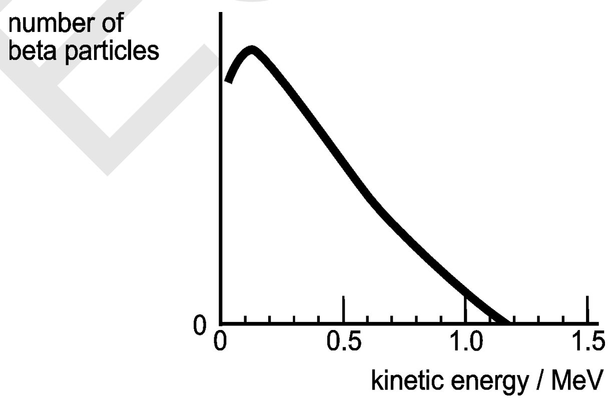

Fig. 2

As Fig. 2 shows, some beta particles have a maximum energy of 1.16 MeV, so this should be the energy released by the process, as with alpha decay. What can have happened to the missing energy for the overwhelming majority of beta particles, which emerge with less energy?

‘I’ve done something terrible: I have predicted an undetectable particle’ (W. Pauli)

In 1929, Niels Bohr suggested that the principle of conservation of energy might not hold for beta decay. Most physicists were reluctant to abandon such a fundamental law. In the following year, Wolfgang Pauli wrote a letter to fellow physicists in a conference in Tübingen in Germany, suggesting that that the results were exactly what you would expect if there was **another** particle released with the beta particle. This ‘extra’ particle would carry off the energy that was missing from the beta particle.

What could this new particle be like? First, the conservation of charge indicates that it must be uncharged. Secondly, calculation of the rest energies of the parent and daughter nuclei involved, together with the 1.16 MeV of energy, suggested that the rest energy, and hence the mass, of the new particle was very small. Within three years Enrico Fermi had devised a theory of beta decay incorporating this uncharged particle, for which he proposed the Italian name ‘neutrino’, or ‘little neutral one’. Building a theory around the neutrino, as Fermi did, was one thing: detecting a tiny uncharged particle, as Pauli had already suggested, was quite another matter.

Detecting the neutrino

Although neutrinos interact with matter very rarely, Fermi’s theory suggested that they could participate in a number of reactions. In 1951 Fred Reines and Clyde Cowan planned to detect anti-neutrinos, the anti-particles of neutrinos, with the reaction $\overline{} + {}^{1}_{1}p \rightarrow {}^{1}_{0}n + {}^{0}_{+1}e$. In this process, an anti-neutrino produced by nuclear reactions interacts with a proton to produce a neutron and a positron. The positron very soon encounters an electron and they annihilate to give a pair of gamma photons; a few microseconds later, the neutron is absorbed by a suitable heavy nucleus and another gamma photon is emitted. The process is shown in Fig. 3.

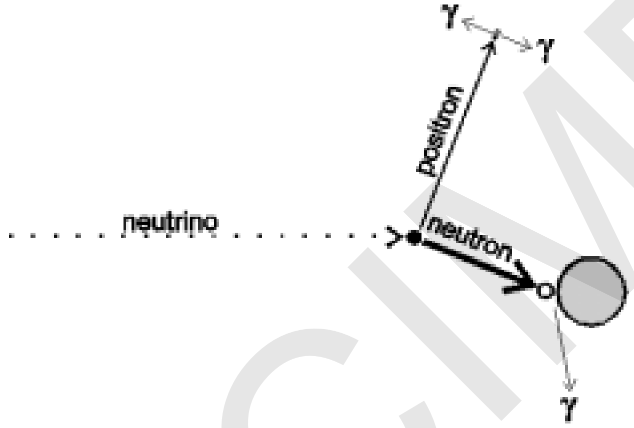

Fig. 3

Reines and Cowan first planned to detect the neutrinos emitted from a nuclear explosion – this was during the 1950s, when atomic bomb tests were a regular occurrence – but they calculated that the more controlled environment of a nuclear reactor should provide a steady anti-neutrino flux of 10^{17} anti-neutrinos m^{-2} s^{-1}. They set up their experiment in 1953, at the Hanford nuclear reactor in Washington State, USA. The detector was a tank of water containing a dissolved salt of the heavy metal cadmium, and the gamma photons produced were detected by photomultiplier tubes outside the tank. If a pair of photons were observed travelling in opposite directions, followed by a single photon less than five microseconds later, then this would be convincing evidence that the reaction had taken place.

Unfortunately, there was a large background count, even when the reactor was shut down, due mainly to cosmic rays. Clyde Cowan later said, ‘It is easy to shield out the noise men make, but impossible to shut out the cosmos. Neutrons and gamma rays from the reactor, which we had feared most, were stopped in our thick walls of paraffin, borax and lead, but the cosmic ray mesons penetrated gleefully, generating backgrounds in our equipment as they passed or stopped in it. We did record neutrino-like signals, but the cosmic rays with their neutron secondaries generated in our shields were 10 times more abundant.’ This made detection of the anti-neutrinos impossible, so Reines and Cowan moved the detector across the USA to the new Savannah River nuclear reactor on the Georgia/South Carolina border. Like the Hanford reactor, this was a military installation built for the construction of nuclear weapons. This location had a well-shielded location for the experiment, 12 metres underground. This greatly improved the signal to noise ratio in the experiment. Despite the low counting rate (about three events per hour), the analysis of these events, with the right delay between the gamma photons, finally demonstrated the existence of the neutrino as a free particle.

[Turn Over

Neutrino astronomy and the solar neutrino problem

Having established the existence of neutrinos, the next target was to attempt to detect the neutrinos predicted to emerge from the Sun from fusion reactions such as ${}^{1}_{1}\text{p} + {}^{1}_{1}\text{p} \rightarrow {}^{2}_{1}\text{H} + {}^{0}_{+1}\text{e} + \nu$. The power produced by the Sun is known to be about 4×10^{26} W, from measurements of the energy reaching Earth. This requires the fusion of 6×10^{11} kg of hydrogen each second. As a consequence, the Sun produces about 2×10^{38} neutrinos every second, which means that billions of neutrinos are streaming through your body each second. In medical terms the low reactivity of neutrinos is a blessing, for only a few thousand neutrinos will transfer their energy to you each year, meaning that the absorbed dose is truly negligible. However, this is a considerable disadvantage when you are trying to detect those neutrinos.

A large neutrino detector, containing 400 m^3 of the dry-cleaning fluid tetrachloroethene (C_2Cl_4), was constructed by Ray Davis in 1966 to count the neutrinos coming from the Sun. This was buried nearly 1.5 km underground, in the Homestake Gold Mine in South Dakota, to eliminate background radiation. One in four of the chlorine atoms present in the tetrachloroethene is of the isotope chlorine-37, and this can absorb a neutrino to give a radioactive argon-37 atom. Observing the low count rate of decaying argon-37 atoms is extremely difficult, but over the past 25 years about 12 decays per month have been detected.

Although it was satisfying to have a significant, measurable result, it troubled astro-physicists because it seemed far too low. Two experiments, one in Baksan in the Caucasus Mountains of Russia and one in Gran Sasso in the Italian Appennine mountains, were designed to check and extend the results. These used large detectors made of gallium, which was predicted to react with less energetic neutrinos than chlorine-37. As with the Homestake experiment, these were buried deep underground to screen the apparatus from other ionising radiation. The results confirmed the Dakota results: there were definitely fewer neutrinos detected from the Sun than had been predicted – about a third as many as expected.

Neutrinos, photons and stars

In the core of a star, fusion reactions such as ${}^{1}_{1}\text{p} + {}^{1}_{1}\text{p} \rightarrow {}^{2}_{1}\text{H} + {}^{0}_{+1}\text{e} + \nu$ generate vast numbers of neutrinos. Gamma photons are produced during the reaction and also in the subsequent annihilation of the positrons with electrons in the core. The photons are continually absorbed and re-emitted by the plasma in the stellar core. As the photons travel out, and are absorbed and re-emitted by cooler regions of the Sun, the average energy per photon decreases. As a consequence, the number of such photons increases more than a thousand times as energy travels from the 6 000 000 K core to the 5800 K surface.

Diffusion of molecules of one gas through another is very slow. This is because a moving molecule constantly collides with others, and rebounds in a random direction, as shown in Fig. 4. The average distance between collisions L is called the mean free path. After N such collisions, an average molecule has had a displacement only $\sqrt{N} \times L$ in magnitude, even though the distance it has travelled is N × L.

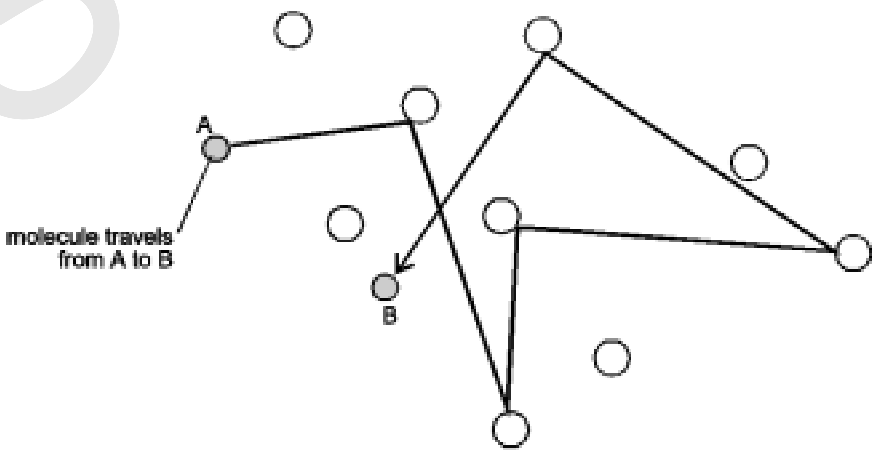

Fig. 4

In very much the same way, the photons take tens of thousands of years to escape from the Sun as they are continually absorbed and re-emitted by ions in the Sun's core, continually changing direction while gradually drifting outwards, as shown in Fig. 5. The neutrinos, generated at the same time, take less than a second to leave the core.

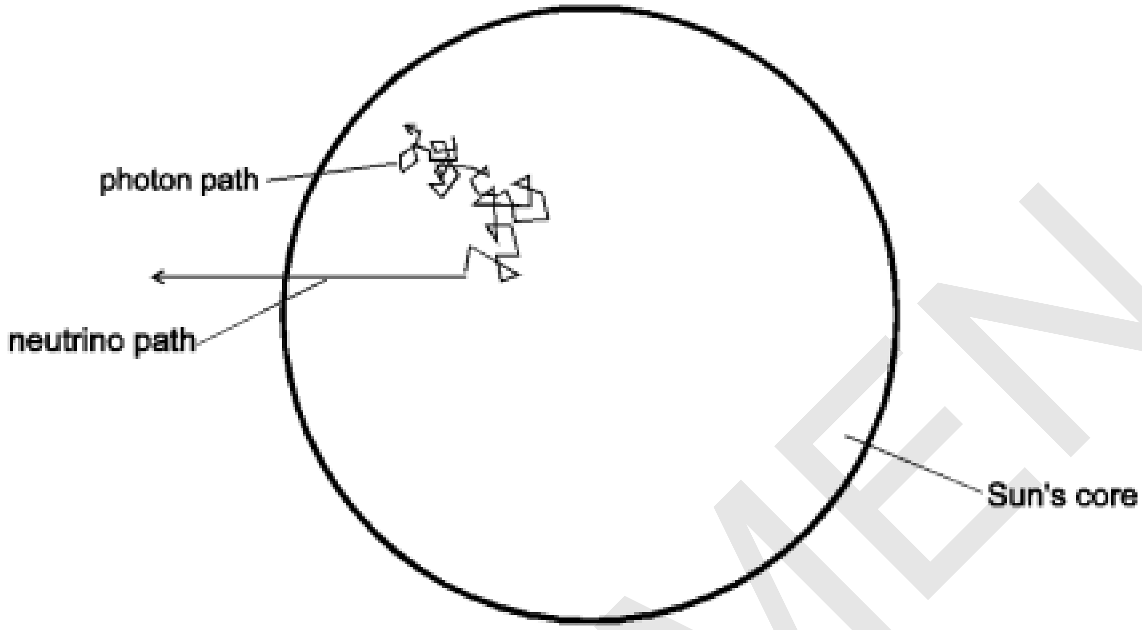

Fig. 5

Fusion in the core of a massive star combines nuclei together until they have all been converted to iron. Then fusion stops, as iron is the most stable nucleus. The star collapses rapidly inwards, creating a supernova. This collapse is predicted to generate an enormous number of neutrinos.

This theoretical fate was dramatically confirmed in February 1987, when a supernova in a neighbouring galaxy, a mere 52 kiloparsecs (170 000 light years) away, was observed. Two hours before any change in the light output had been detected; a burst of 11 neutrinos had been detected in Japan and 8 in the USA. These numbers may seem tiny, but as only about one neutrino in 10^{18} actually interacts with matter, the number detected was consistent with the theoretical prediction for a supernova core collapse at a distance of 52 kiloparsecs from Earth.

End of Article

Reines & Cowan, viz.Reines, Cowan et al 1960 Physical Review 117 159-173

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Sources:

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