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PHYSICS
HIGHER LEVEL
PAPER 3

Candidate session number

Friday 7 November 2014 (afternoon)

1 hour 15 minutes

Examination code

8	8	1	4	–	6	5	0	3

INSTRUCTIONS TO CANDIDATES

- Write your session number in the boxes above.
- Do not open this examination paper until instructed to do so.
- Answer all of the questions from two of the Options.
- Write your answers in the boxes provided.
- A calculator is required for this paper.
- A clean copy of the ***Physics*** *Data Booklet* is required for this paper.
- The maximum mark for this examination paper is *[60 marks]*.

Option	**Questions**
Option E — Astrophysics	1 – 5
Option F — Communications	6 – 10
Option G — Electromagnetic waves	11 – 15
Option H — Relativity	16 – 20
Option I — Medical physics	21 – 23
Option J — Particle physics	24 – 27

48 pages

Option E — Astrophysics

1. This question is about the night sky.

(a) Distinguish between a stellar cluster and a constellation. *[2]*

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(b) Describe the apparent motion of stars in the sky over a period of 24 hours. *[1]*

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(Option E continues on the following page)

(Option E continued)

2. This question is about stellar radiation and stellar types.

Alnilam and Bellatrix are two stars in the constellation of Orion. The table gives information on each of these stars. $L_{\odot}$ is the luminosity of the Sun and $R_{\odot}$ is the radius of the Sun.

	Apparent magnitude	**Absolute magnitude**	**Surface temperature**	**Luminosity**	**Radius**
Alnilam	+1.68	−6.37	27 000 K	$275\,000L_{\odot}$	$24R_{\odot}$
Bellatrix	+1.62	−2.37	T_{B}	$6400L_{\odot}$	$6R_{\odot}$

(a) (i) Explain how Alnilam has a similar apparent magnitude to Bellatrix but a smaller absolute magnitude. *[2]*

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(ii) Calculate the surface temperature T_{B} of the star Bellatrix. *[3]*

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(Option E continues on the following page)

(Option E, question 2 continued)

(b) Using a telescope based on Earth, an observer estimates the distance to Alnilam using the stellar parallax method.

(i) Describe the stellar parallax method. *[2]*

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(ii) Determine whether the stellar parallax method can be used to estimate the distance of Alnilam from Earth. *[3]*

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(Option E continues on the following page)

(Option E continued)

3. This question is about cosmology.

Newton assumed that the universe was infinite, uniform and static. The Big Bang model suggests space and time originated at one point around 14 billion years ago. At this time the temperature was very high.

(a) Olbers suggested that if Newton was correct then the sky should never be dark. Explain Olbers' paradox quantitatively. *[3]*

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(b) In 1965, Penzias and Wilson discovered cosmic radiation with a wavelength that corresponded to a temperature of around 3 K. Outline how cosmic radiation in the microwave region is consistent with the Big Bang model. *[2]*

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(c) Suggest how the Big Bang model provides a resolution to Olbers' paradox. *[2]*

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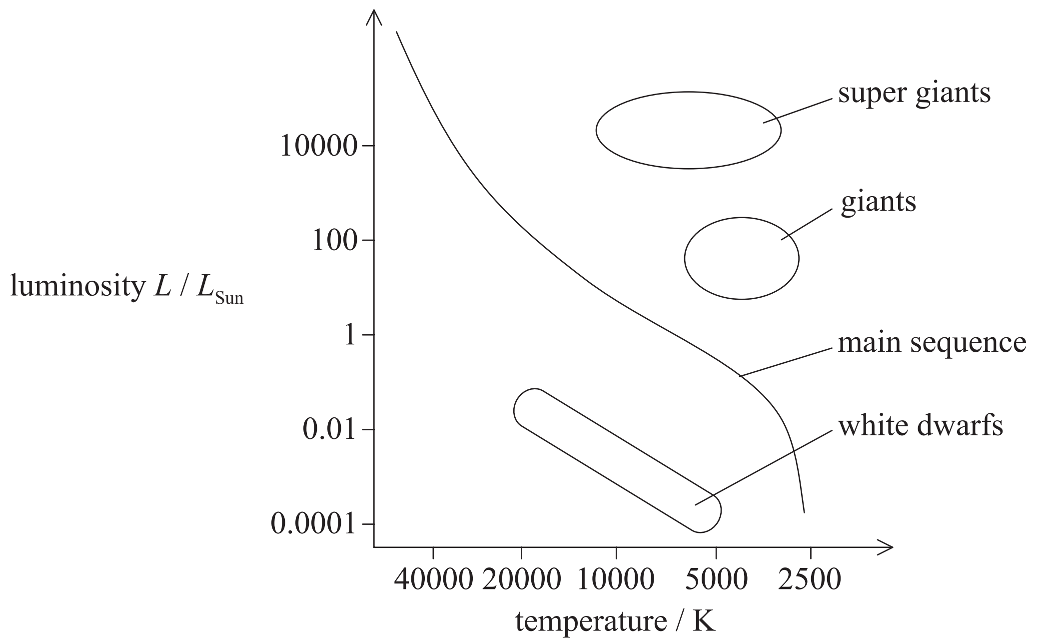
(Option E continued)

4. This question is about the Hertzsprung–Russell (HR) diagram and stellar evolution.

The star Phi-1 Orionis is a large star on the main sequence with a mass of approximately 18 solar masses.



(a) Calculate the luminosity of Phi-1 Orionis in terms of the luminosity of the Sun. Assume that $n = 3.5$ in the mass–luminosity relation. *[2]*

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(Option E continues on the following page)

(Option E, question 4 continued)

(b) The Sun is expected to have a lifespan of around 10^{10} years. With reference to the equilibrium between radiation pressure and gravitational pressure, discuss why Phi-1 Orionis will use up its hydrogen at a faster rate than the Sun. *[2]*

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(c) (i) Using the HR diagram on page 6, draw the evolutionary path of Phi-1 Orionis as it leaves the main sequence. *[1]*

(ii) Outline, with reference to the Oppenheimer–Volkoff limit, the fate of Phi-1 Orionis. *[1]*

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(Option E continues on the following page)

(Option E continued)

5. This question is about the Hubble constant.

A recent estimate for the value of the Hubble constant is $70\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$.

(a) Estimate, in seconds, the age of the universe. *[2]*

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(b) The wavelength of the lines in the absorption spectrum of hydrogen is 656.3 nm when measured on Earth. Analysis of light from a distant galaxy shows that the same line has a wavelength of 725.6 nm. Determine the recessional velocity of the distant galaxy. *[2]*

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End of Option E

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Answers written on this page
will not be marked.

Option F — Communications

6. This question is about radio communication.

A signal wave can modulate a carrier wave using either amplitude modulation (AM) or frequency modulation (FM).

(a) (i) Distinguish between amplitude modulation and frequency modulation. *[2]*

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(ii) State why carrier waves are modulated. *[1]*

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(iii) Sketch the waveform that results when a signal wave modulates a carrier wave of higher frequency. Include at least **one** cycle of the amplitude modulation. *[2]*

(Option F continues on the following page)

(Option F, question 6 continued)

(b) Identify **one** advantage and **one** disadvantage of AM radio communication compared to FM radio communication. *[2]*

Advantage:

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Disadvantage:

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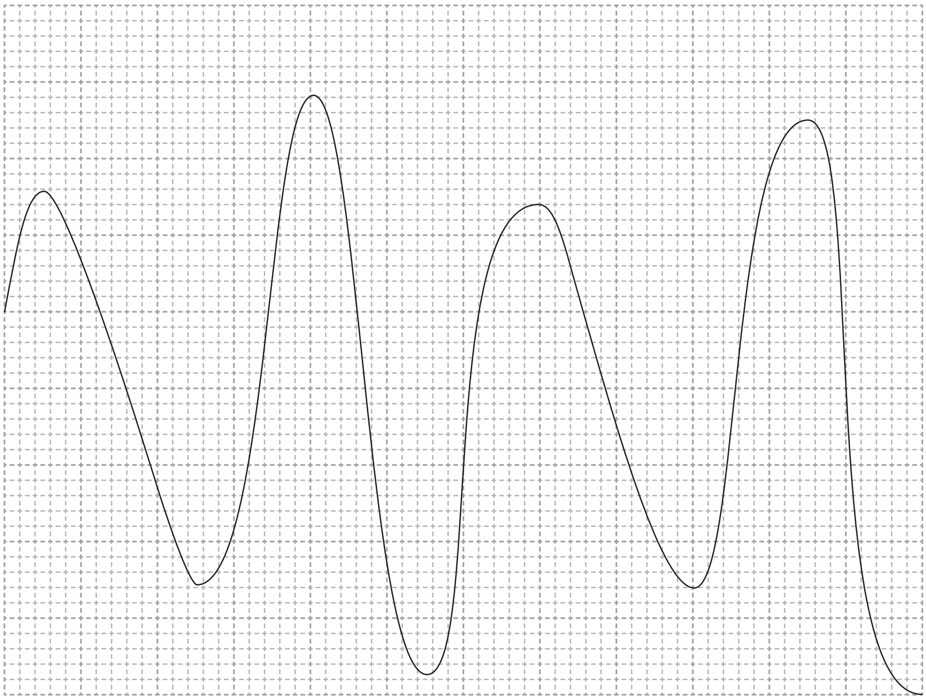
(Option F continues on the following page)

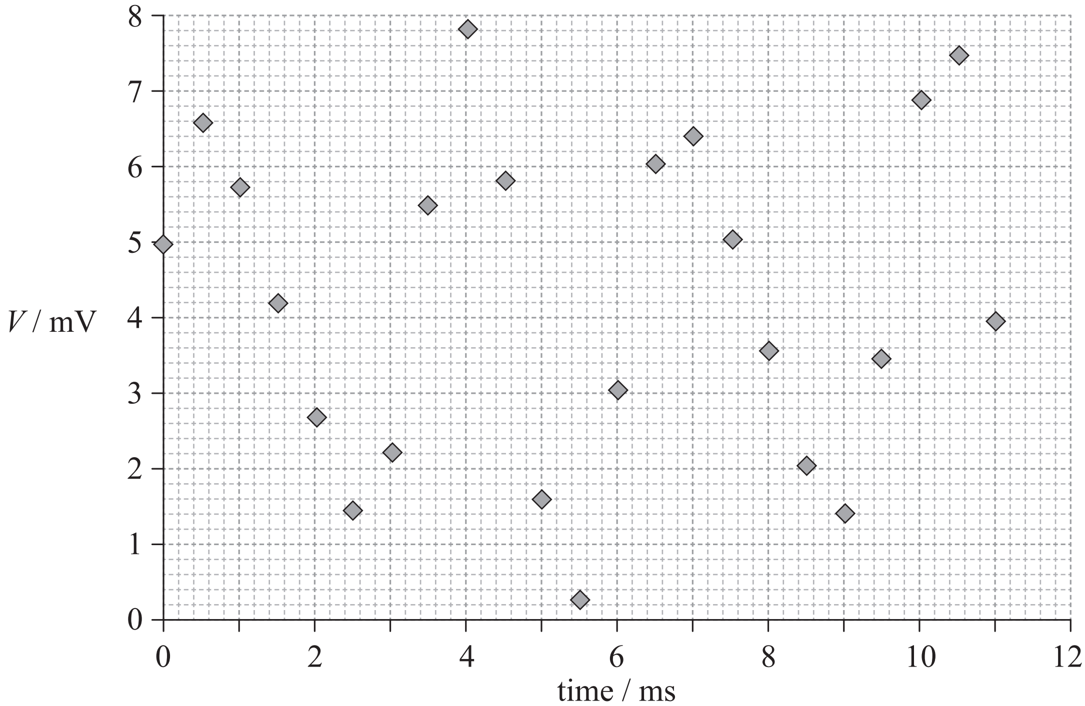
(Option F continued)

7. This question is about digital signals.

Graph 1 shows the original waveform of a sound wave.



Graph 2 shows the voltage of this wave at the sampling points.



(Option F continues on the following page)

(Option F, question 7 continued)

The input signal is converted into a 4-bit binary signal, according to the following rule.

Input signal / mV	**4-bit binary conversion**
$0 \le V < 0.5$	0000
$0.5 \le V < 1.0$	0001
$1.0 \le V < 1.5$	0010
$1.5 \le V < 2.0$	0011
⋮	⋮
$7.5 \le V < 8.0$	1111

(a) Calculate the sampling frequency. *[1]*

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(b) Determine the 4-bit binary signal when $t = 4.5\,\text{ms}$. *[1]*

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(c) State and explain **one** change to this system which will allow the output signal that was reconstructed from the binary signal to match the original analogue signal more closely. *[2]*

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(Option F continues on the following page)

(Option F continued)

8. This question is about optic fibres.

An optic fibre consists of a thin glass fibre surrounded by a cladding material. The refractive index of the glass is 1.62.

(a) (i) Calculate the critical angle for this optic fibre. *[1]*

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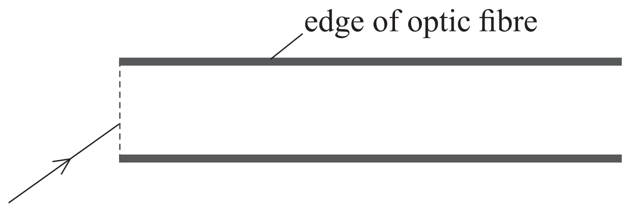
(ii) The diagram shows a straight optic fibre. Sketch the passage of a ray of light through the fibre. *[2]*



(b) The input power to the fibre is 150 mW. The attenuation per unit length of the glass fibre is 12.0 dB km^{-1}. When the light has travelled a distance l its power has fallen to 3.00 mW, at which point amplification of the signal is required. Determine l. *[2]*

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(Option F continues on the following page)

(Option F, question 8 continued)

(c) The variation with time t of the input power to an optic fibre of length l is shown in diagram 1. The variation with time t of the output power from the optic fibre is shown in diagram 2. The output power in diagram 2 is not to the same scale as the input power on diagram 1.

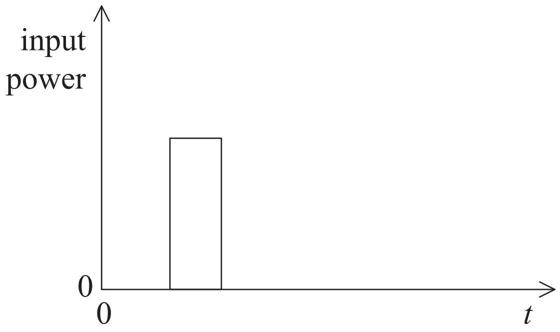

Diagram 1

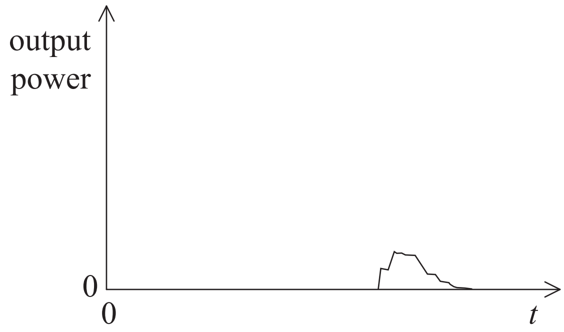

Diagram 2

The output power is much smaller than the input power because energy is absorbed as the light passes along the optic fibre.

(i) One difference between the shape of the input and output signals is that the output signal is noisier than the input signal. State and explain **one** other difference between the shape of the input signal and the output signal. *[2]*

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(ii) Describe how the output signal can be restored to its original shape. *[2]*

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(Option F continues on the following page)

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(Option F continued)

9. This question is about satellite communication.

(a) State what is meant by a geostationary satellite. *[2]*

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(b) Discuss **one** advantage and **one** disadvantage of a polar-orbiting satellite compared to a geostationary satellite when it is used for mapping the Earth's surface. *[2]*

Advantage: . . . .
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Disadvantage: . . . .
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(c) A ground station on Earth transmits to a satellite on an up-link frequency. The satellite transmits back to Earth on a down-link frequency. Explain **one** reason why these two frequencies should **not** be the same. *[1]*

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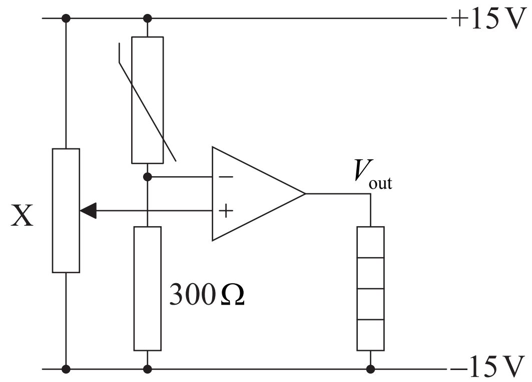
(Option F continues on the following page)

(Option F continued)

10. This question is about an operational amplifier (op-amp).

An op-amp is used as a comparator in a circuit, as shown.



The circuit is used to monitor the temperature in a greenhouse. The resistance of a thermistor decreases as its temperature increases.

(a) Explain how the potential at the inverting input changes as the temperature decreases. *[2]*

(b) Describe the purpose of component X in the circuit. *[1]*

(Option F continues on the following page)

(Option F, question 10 continued)

When the potential of the non-inverting input is set at 0 V, the heater switches on at a temperature of around 10 °C. The ideal temperature to grow plants in the greenhouse is 18 °C or greater. At 18 °C the resistance of the thermistor is 193 Ω.

(c) Show that the potential at the non-inverting input should be set to around 3 V to ensure the heating element turns on when the temperature is less than 18 °C. *[2]*

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End of Option F

Option G — Electromagnetic waves

11. This question is about convex lenses.

(a) A convex (converging) lens is used to project an image onto a screen. The focal length of the lens is 10 cm. The object is placed at a distance of 15 cm from the centre of the lens on the principal axis.

(i) Define *principal axis*. *[1]*

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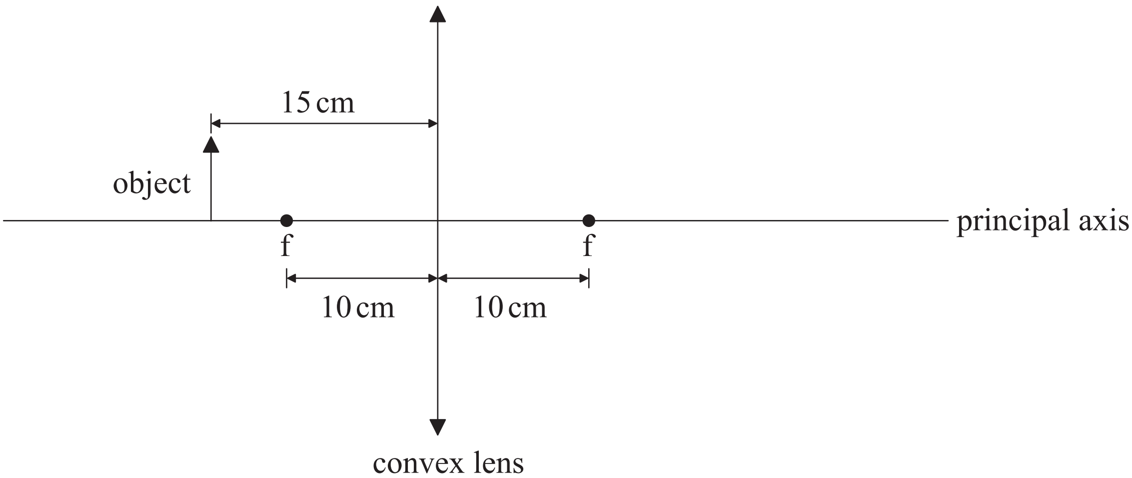
(ii) Construct rays to locate the position of the image. *[3]*



(iii) Identify the nature of the image. *[1]*

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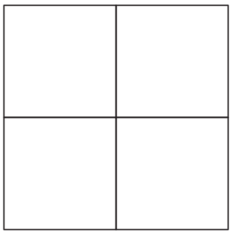
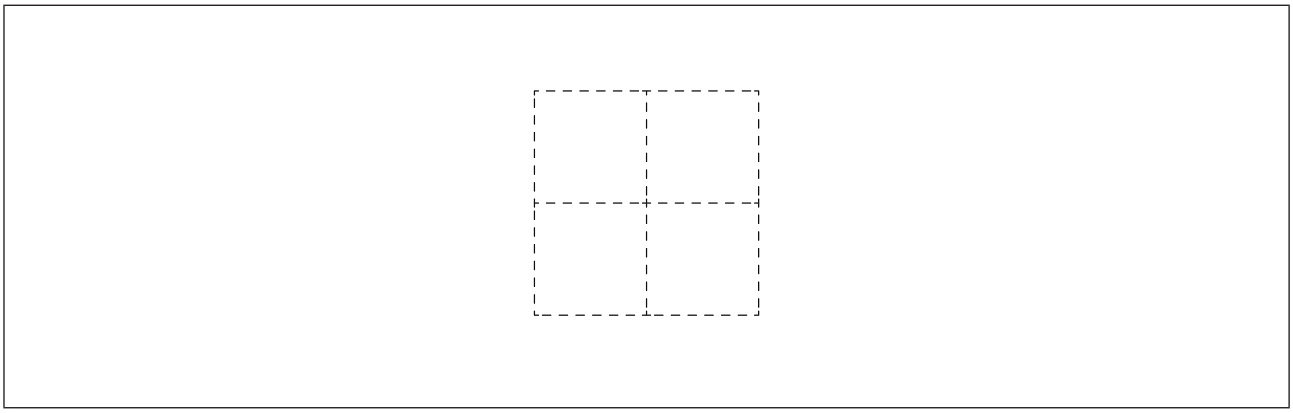
(Option G continues on the following page)

(Option G, question 11 continued)

(b) Another object, as shown, is positioned so that the centre of the object lies on the principal axis of the lens. The object is normal to the principal axis. The lens has not been corrected for spherical aberration.



The diagram shows what would be seen on the screen if the lens produced no aberrations in the image.



(i) The lens is covered with a wide aperture. Using the diagram, sketch the likely appearance of the image if the lens **produces** spherical aberrations. *[2]*

(ii) Outline why reducing the size of the aperture will reduce the effects of spherical aberration. *[2]*

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(Option G continues on the following page)

(Option G continued)

12. This question is about lasers.

(a) Outline, in terms of the production of laser light, what is meant by

(i) monochromatic. *[1]*

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(ii) population inversion. *[1]*

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(b) Lasers are widely used in medicine. Outline **one** use of lasers in this field. *[2]*

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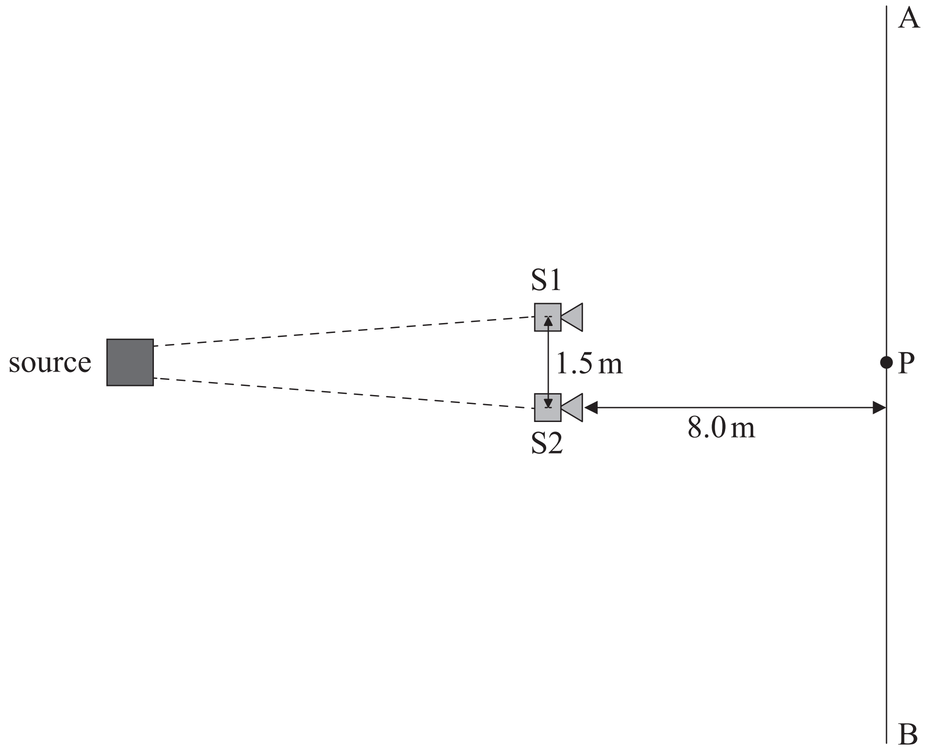
(Option G continues on the following page)

(Option G continued)

13. This question is about the interference of sound waves.

Two loudspeakers, S1 and S2, each emit a musical note of frequency 2.5 kHz with identical signal amplitude. Point P lies on the line AB and is equidistant from S1 and S2. The speakers are placed 1.5 m apart from each other and 8.0 m from line AB. The speed of sound is 330 m s^{-1}.



A person walking in a straight line from A to B observes that the intensity of sound alternates between high and low.

(a) With reference to interference, explain why the intensity of sound alternates along line AB. *[3]*

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(Option G continues on the following page)

(Option G, question 13 continued)

(b) The sound has a maximum intensity at P. Calculate the distance along line AB to the next intensity maximum when S1 and S2 emit a musical note of frequency 2.5 kHz. *[2]*

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(c) S1 and S2 are moved so that they are now 3.0 m apart. They remain at the same distance from line AB. Discuss the changes, if any, in the rate at which the intensity of sound alternates when a person is walking along line AB at half the speed. *[2]*

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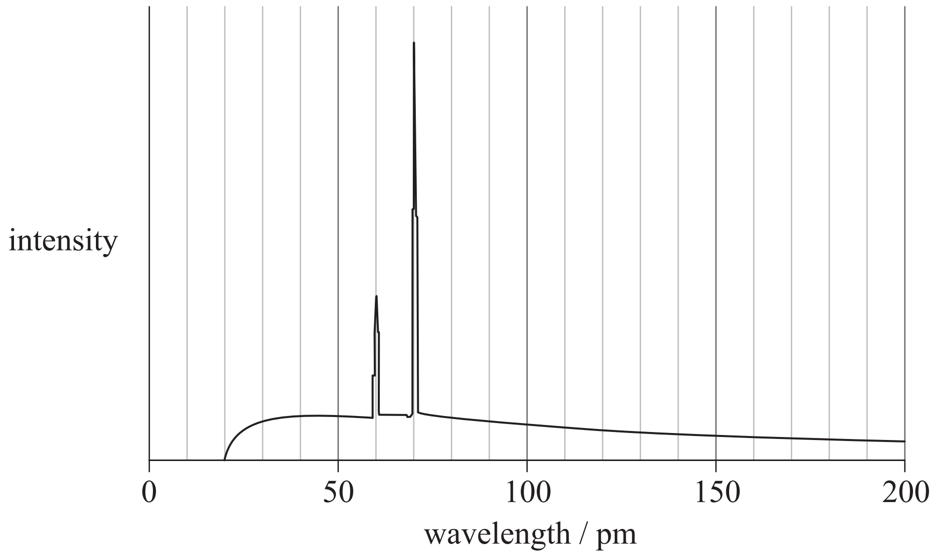
(Option G continues on the following page)

(Option G continued)

14. This question is about X-ray diffraction.

(a) Electrons strike rhodium after acceleration through a potential difference. The X-ray spectrum emitted is shown.



(i) Calculate the potential difference through which the electrons were accelerated. *[2]*

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(ii) Explain the presence of the characteristic peaks of the spectrum. *[2]*

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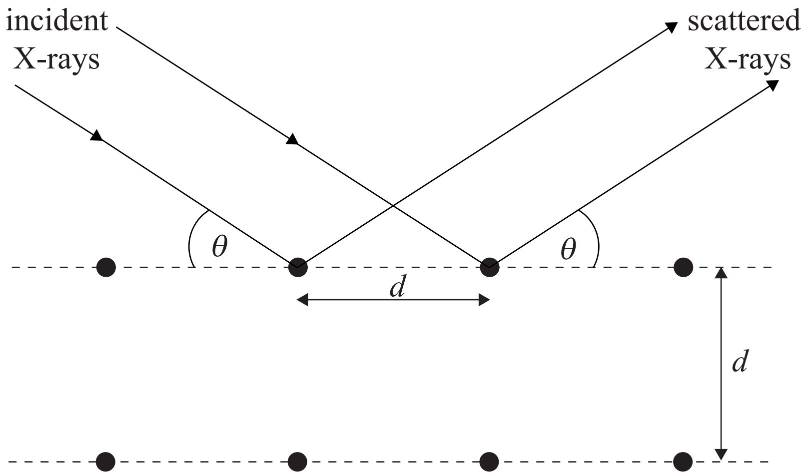
(Option G continues on the following page)

(Option G, question 14 continued)

(b) X-rays may be used to determine the structure of a crystal. A beam of X-rays of wavelength 200 pm is incident on the surface of a crystal. The separation d of the atoms is 3.6×10^{-10} m.



Calculate the angle θ for which the second order maximum of the diffraction pattern appears. *[2]*

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(Option G continues on the following page)

(Option G continued)

15. This question is about thin-film interference.

A thin film of oil of constant thickness floats on the surface of water. The refractive indices *n* of each material is shown on the diagram.

(a) Explain why the film of oil appears to show coloured fringes. *[2]*

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(b) When white light is normally incident on the surface of the oil, the film appears green to an observer. The wavelength of green light in air is 520 nm. Calculate the thickness of the film of oil. *[2]*

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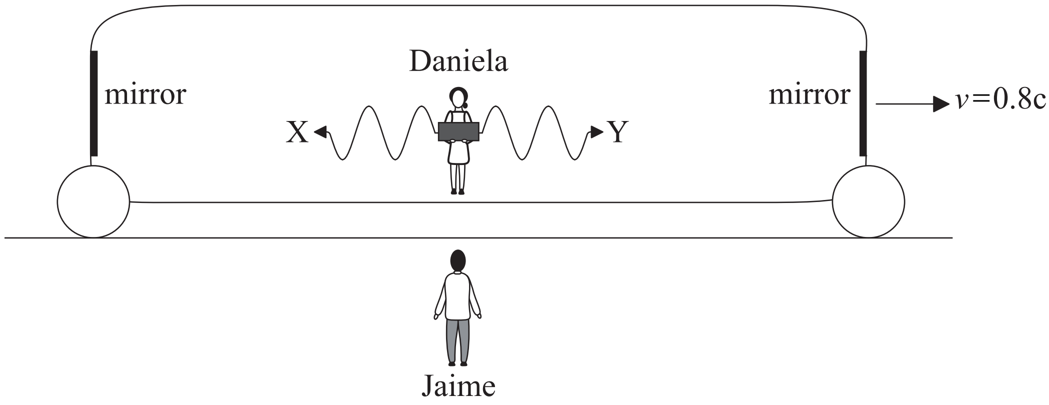
End of Option G

Option H — Relativity

16. This question is about simultaneity.

Daniela is standing in the middle of a train that is moving at a constant velocity relative to Jaime, who is standing on the platform. At the moment the train passes Jaime, two beams of light, X and Y, are emitted simultaneously from a device held by Daniela. Both beams are reflected by mirrors at the end of the train and then return to Daniela.



(a) State and explain the order of arrival of X and Y at the mirrors according to Jaime. *[3]*

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(b) Outline whether the return of X and Y to Daniela are simultaneous according to Jaime. *[2]*

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(Option H continues on the following page)

(Option H continued)

17. This question is about a light clock.

(a) One of the postulates of special relativity refers to the speed of light. State the other postulate of special relativity. *[1]*

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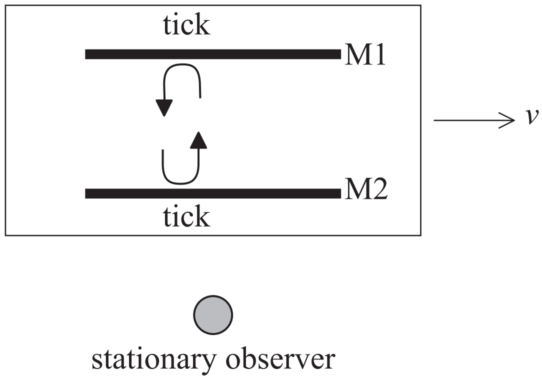
(b) In a light clock, a beam of light is reflected between two parallel mirrors M1 and M2.



The time interval between successive reflections at M2 according to an observer **at rest relative to the light clock** is t. This light clock is moving at velocity v relative to the stationary observer.

(i) Show that the time t' between successive reflections at M2 in this light clock as measured by the stationary observer is $t' = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}t$. *[3]*

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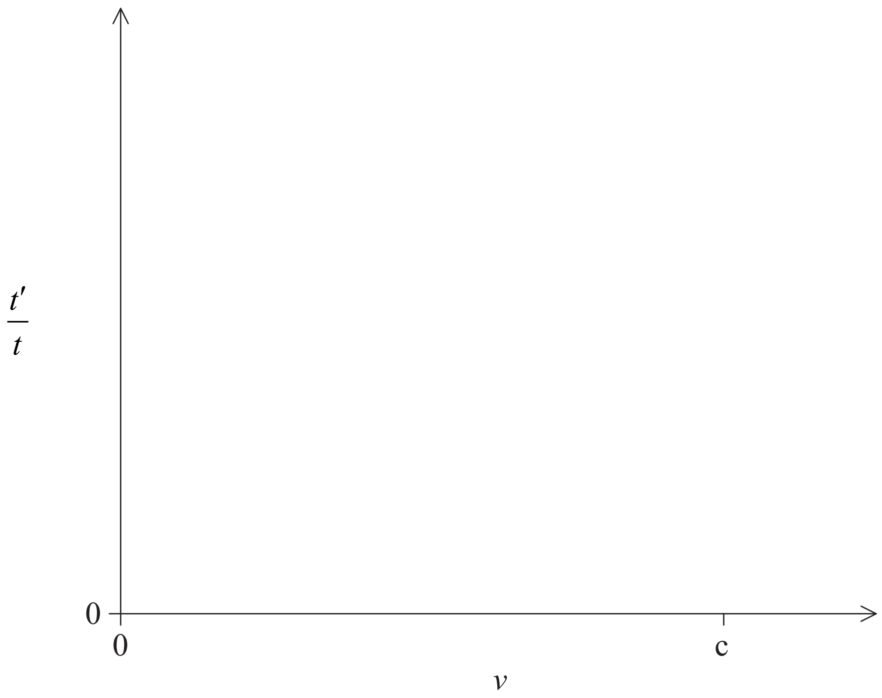
(Option H continues on the following page)

(Option H, question 17 continued)

(ii) Using the axis, sketch a graph to show how the ratio $\frac{t'}{t}$ varies with v. You should add key values to your graph. *[2]*



(Option H continues on the following page)

(Option H continued)

18. This question is about muon decay.

Muons are produced in the Earth's atmosphere at a height of around 10 km above the surface. They then travel at a speed of around 0.98c towards the Earth. The average time for a muon to decay is approximately 2.2 μs, according to observers at rest relative to the muon.

(a) Deduce that few muons would be expected to arrive at the surface of the Earth if non-relativistic mechanics are assumed. *[2]*

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(b) Many muons are observed to reach the surface of the Earth.

(i) Calculate the average decay time of a muon as observed by an observer on the surface of the Earth. *[2]*

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(ii) Explain, with a calculation, why many muons reach the surface of the Earth before they have decayed. *[2]*

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(Option H continues on the following page)

(Option H continued)

19. This question is about relativistic momentum and energy.

An electron and a positron travel towards each other in a straight line in a vacuum. A positron is a positively charged electron.

The speed of each particle, as measured by an observer in the laboratory, is 0.85c. The value of the Lorentz factor at this speed is approximately 1.9.

(a) Calculate the speed of the positron as measured in the frame of reference of the electron. *[2]*

(Option H continues on the following page)

(Option H, question 19 continued)

(b) The electron and positron annihilate each other, creating two photons in the process. Each of the photons transfers the same quantity of energy.

(i) Calculate the total energy in the reaction. *[1]*

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(ii) Outline why two photons must be released in this collision. *[2]*

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(iii) Determine the frequency of one of the photons. *[2]*

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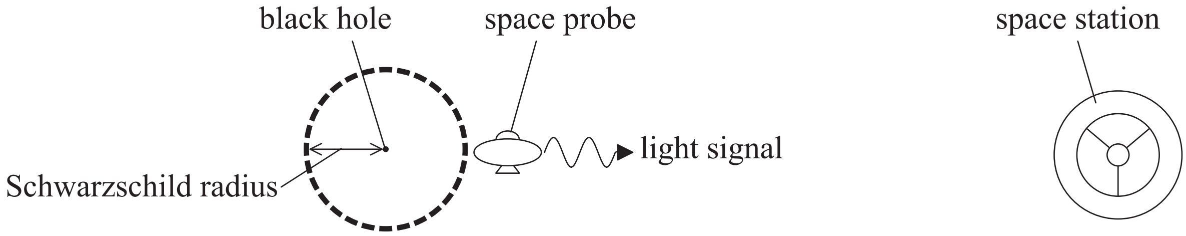
(Option H continues on the following page)

(Option H continued)

20. This question is about black holes.

A space probe is stationary in the gravitational field of a black hole.



The mass of the black hole is 4.5×10^{31} kg. The space probe is emitting a pulse of blue light at a time interval of 1.0 seconds as measured on the space probe. The light is received by an observer on a distant space station that is stationary with respect to the space probe.

(a) Explain why the light reaching the space station will be red-shifted. *[3]*

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(b) The time between the pulses as measured by the observer on the distant space station is found to be 1.5 s. Calculate the distance of the space probe from the black hole. *[3]*

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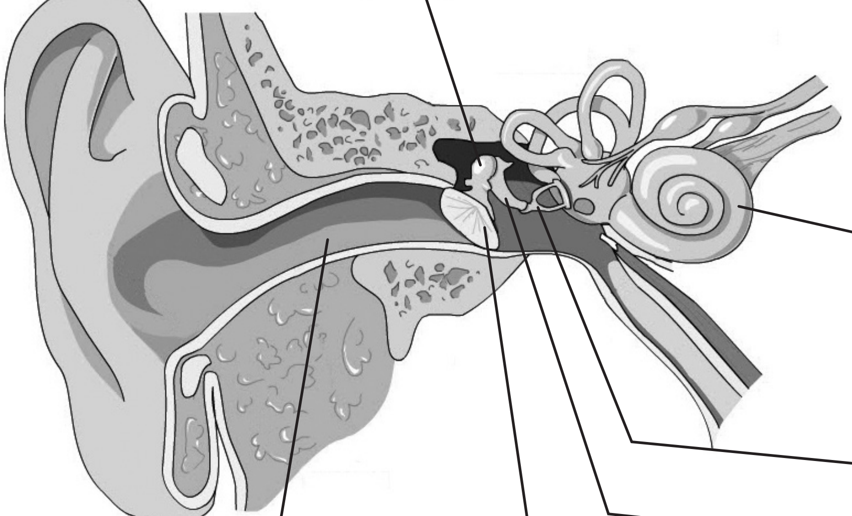
End of Option H

Option I — Medical physics

21. This question is about the ear and hearing.

The diagram shows parts of the human ear.



(a) Sound waves that pass from the auditory canal can be transmitted into the cochlea rather than being reflected at the boundary.

(i) Using the diagram, label the position of the oval window. *[1]*

(ii) Explain how the structure of the middle ear allows sound waves to be transmitted to the cochlear fluid. *[2]*

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(Option I continues on the following page)

(Option I, question 21 continued)

(b) A construction worker is exposed to sound levels of 105 dB continuously over an eight hour period.

(i) Show that the intensity of sound corresponding to noise of 105 dB is about $30\,\text{mW}\,\text{m}^{-2}$. *[2]*

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(ii) Noise-induced permanent hearing loss can occur when a person is exposed to sounds of an intensity level greater than 90 dB for extended periods of time. Calculate the fraction of power of the noise that needs to be prevented from entering the ear of the construction worker to prevent permanent hearing loss. *[2]*

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(Option I continues on the following page)

(Option I continued)

22. This question is about medical imaging using X-rays.

(a) The table shows the attenuation coefficient μ (mu) for different parts of the body.

μ_{air}	$0\,cm^{-1}$
μ_{muscle}	$0.180\,cm^{-1}$
μ_{blood}	$0.178\,cm^{-1}$
μ_{bone}	$0.48\,cm^{-1}$

(i) Define *attenuation coefficient*. *[1]*

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(ii) Calculate the half-value thickness for blood. *[2]*

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(Option I continues on the following page)

(Option I, question 22 continued)

(b) An X-ray scan is taken of a patient to examine the flow of blood through their arm. X-rays of intensity I are incident on an equal thickness of blood and muscle. The intensity of the X-rays is measured after passing through the blood and muscle respectively.

(i) Calculate the ratio $\frac{I_{\text{blood}}}{I_{\text{muscle}}}$ for 1cm of tissue. *[2]*

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(ii) Suggest why an X-ray scan does not allow for the differentiation between muscle and blood. *[2]*

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(c) A contrast medium containing iodine is injected into the patient. This increases the attenuation coefficient of blood so that the difference between the intensities of blood and muscle is greater than 2%. The blood can now be observed on an X-ray scan. Determine the minimum increase in μ_{blood} that will enable a sharper contrast to be observed between an equal thickness of muscle and blood. *[3]*

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(Option I continues on the following page)

(Option I, question 22 continued)

(d) X-rays are a form of ionizing radiation. To reduce the danger to a patient, the intensity of X-rays are kept to a minimum. Describe how enhancement allows for low intensity X-rays to be used. *[2]*

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23. This question is about the use of radioactive isotopes.

(a) Radiologists working with radioactive sources wear a film badge. Discuss the function of a film badge. *[3]*

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(b) Patients suffering from prostate cancer can experience metastatic bones. As part of the cancer treatment, patients are injected with an isotope of strontium which is readily taken up by the bones.

The table shows the half-life and emission information for strontium-89 (Sr-89) and strontium-90 (Sr-90).

	Strontium-89 (Sr-89)	**Strontium-90 (Sr-90)**
Physical half-life	50.5 days	29.1 years
Biological half-life	50 days	around 30 years
Type of emission	low energy beta (β) particles with a range of 8.0 mm	high energy beta (β) particles

(Option I continues on the following page)

(Option I, question 23 continued)

Beta particles have a quality factor of 1.

(i) State the meaning of the term quality factor. *[1]*

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(ii) Using the information in the table, outline why Sr-89 is preferred to Sr-90 in the treatment of bone cancers. *[2]*

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(iii) Calculate the effective half-life of Sr-89 in a patient. *[2]*

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(iv) State, in terms of range, **two** reasons why Sr-89 is the more suitable choice of isotope to be used in the treatment of bone cancers. *[2]*

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(Option I continues on the following page)

(Option I, question 23 continued)

(c) One of the side effects of the use of Sr-89 is the reduction of white blood cells in the body, leaving the patient prone to infections. Outline **one** ethical implication of the choice between using Sr-89 to treat bone cancer and not carrying out treatment. *[1]*

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End of Option I

Option J — Particle physics

24. This question is about fundamental interactions and elementary particles.

(a) (i) Identify the type of fundamental interactions associated with the exchange particles in the table. *[2]*

Exchange particle	Fundamental interaction
Photon	
Pi meson, π^+	

(ii) State why π^+ mesons are **not** considered to be elementary particles. *[1]*

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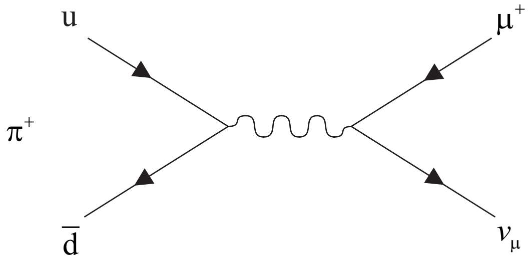
(Option J continues on the following page)

(Option J, question 24 continued)

(b) The Feynman diagram represents the decay of a π^+ meson into an anti-muon and a muon neutrino.



(i) Identify the exchange particle associated with this decay. *[1]*

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(ii) Deduce that this decay conserves baryon number. *[2]*

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(iii) π^+ mesons have a mass of the order of magnitude of around 100 MeV c^{-2}. Show that the range of interactions of π^+ mesons is around 10^{-15} m. *[2]*

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(Option J continues on the following page)

(Option J, question 24 continued)

(iv) Describe why π^+ mesons are thought to be responsible for the strong nuclear force. *[1]*

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(Option J continues on the following page)

(Option J continued)

25. This question is about particle accelerators.

(a) In a large electron–positron collider, electrons are accelerated to very high speeds and collide with stationary positrons. This results in the release of π mesons as shown.

$$e^- + e^+ \rightarrow \pi^+ + \pi^-$$

The rest mass of π mesons is $105\,\text{MeV}\,c^{-2}$.

Determine the minimum energy given to the electrons for this reaction to take place. *[2]*

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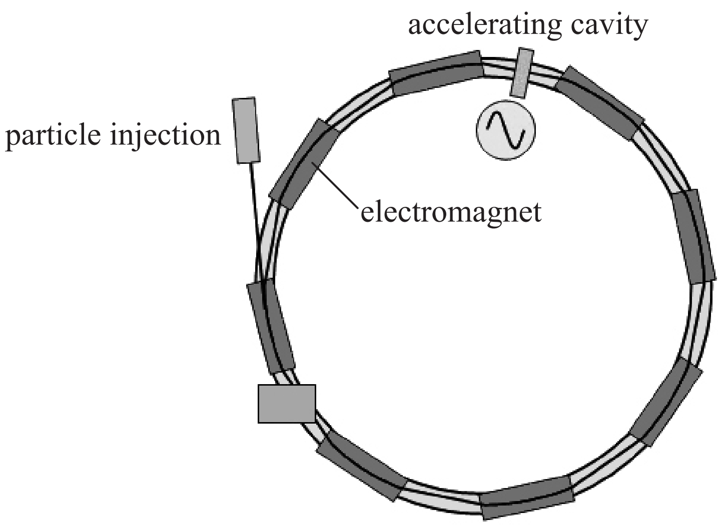
(b) A synchrotron can be used to accelerate electrons and positrons so that they collide together at high speeds. A schematic diagram of a synchrotron is shown.



(Option J continues on the following page)

(Option J, question 25 continued)

(i) Outline the function of the electric field at the point of particle injection. *[2]*

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(ii) Describe why electromagnets are used in a synchrotron rather than permanent magnets. *[2]*

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(iii) The Tevatron was a large synchrotron with a ring circumference of 6.28 km. With reference to bremsstrahlung (braking) radiation, describe why the synchrotron ring needs to have such a large radius. *[2]*

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(Option J continues on the following page)

(Option J continued)

26. This question is about experimental evidence of quarks.

Electrons are accelerated towards a fixed nucleus. The electrons can be scattered by nuclei and nucleons in different ways depending on the incident energy of the electron.

(a) Outline how deep inelastic scattering is used in particle physics. *[2]*

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(b) (i) Calculate the accelerating potential required for deep inelastic scattering off a neutron with a diameter of 10^{-15} m. *[3]*

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(ii) A neutron is a particle with no charge and a spin of $\frac{1}{2}$. Using this information, show that the quark content of a neutron is udd. *[2]*

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(Option J continues on the following page)

(Option J, question 26 continued)

(c) The energy of electrons can be changed. Explain, with reference to the incident energies of the electrons, **two** other types of scattering which may be observed. *[2]*

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(Option J continues on the following page)

(Option J continued)

27. This question is about cosmology and the early universe.

After its formation the universe expanded rapidly, cooling as it did so.

(a) At one stage in its development, the universe contained almost equal numbers of particles and antiparticles. Observation of the recent universe suggests that the antiparticles have largely disappeared. Suggest a mechanism for this observation. *[2]*

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(b) At a later stage nucleosynthesis occurs. Energies of 0.1 MeV are required for this process to predominate in the universe. Determine the temperature, in Kelvin, at which large-scale nucleosynthesis takes place. *[2]*

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End of Option J