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PHYSICS
HIGHER LEVEL
PAPER 3

Candidate session number

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Tuesday 7 May 2013 (afternoon)

1 hour 15 minutes

Examination code

2	2	1	3	–	6	5	1	5

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 E — Astrophysics

E1. This question is about stars.

(a) Define *absolute magnitude*. *[1]*

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(b) The table shows data for two stars, X and Y.

	Apparent brightness / $W\,m^{-2}$	**Absolute magnitude**
Star X	2.5×10^{-8}	– 5.4
Star Y	8.1×10^{-9}	– 6.3

Use the data to explain which star

(i) appears brighter from Earth. *[1]*

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(ii) is closer to Earth. *[1]*

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(This question continues on the following page)

(Question E1 continued)

(c) The luminosity of star X is 4.9×10^{30} W and its spectral class is M.

(i) Determine the distance of star X from Earth. *[2]*

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(ii) Estimate the radius of star X. *[3]*

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(iii) Suggest the type of star X. *[2]*

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(This question continues on the following page)

(Question E1 continued)

(d) Outline how a study of the spectrum of star X gives information about its chemical composition. *[2]*

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E2. This question is about cosmology.

(a) Cosmic microwave background radiation was discovered by Penzias and Wilson in 1964. State **two** characteristics of the cosmic microwave background radiation. *[2]*

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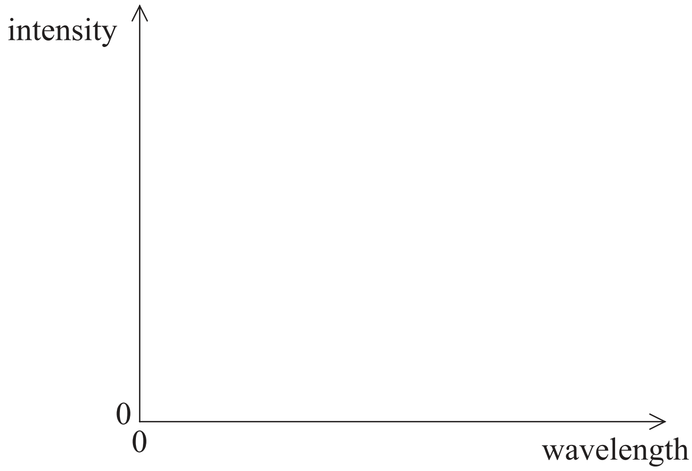
(Question E2 continued)

(b) (i) Using the axes below, sketch a graph to show the variation with wavelength of the intensity of the cosmic background radiation. *[2]*



(ii) Explain how the graph may be used to determine the temperature of the cosmic background radiation. *[2]*

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(iii) Discuss how the discovery of the cosmic background radiation provides evidence for the Big Bang. *[2]*

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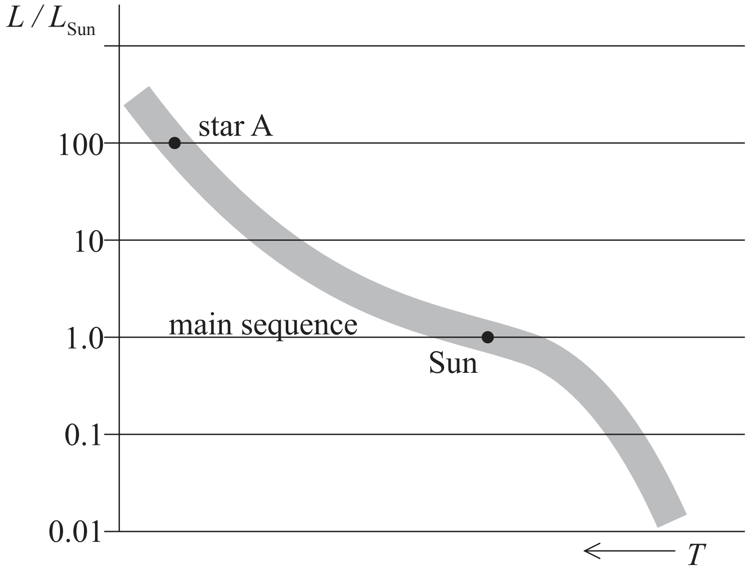
E3. This question is about stellar evolution.

(a) The Hertzsprung–Russell (HR) diagram shows the Sun, a star A and the main sequence.



Using the mass–luminosity relation $L \propto M^{3.5}$, determine the ratio of the mass of star A to the mass of the Sun. *[2]*

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(This question continues on the following page)

(Question E3 continued)

(b) Star A will leave the main sequence and will evolve to become a neutron star. State the

(i) change in star A that marks its departure from the main sequence. *[1]*

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(ii) range of mass of a neutron star. *[1]*

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E4. This question is about Hubble's law.

(a) State Hubble's law. *[1]*

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(b) Light from the galaxy M31 received on Earth shows a blue-shift corresponding to a fractional wavelength shift $\frac{\Delta\lambda}{\lambda}$ of 0.001.

(i) Calculate the velocity of M31 relative to Earth. *[2]*

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(ii) The distance to M31 from Earth is 0.77 Mpc. Estimate, using the answer to (b)(i), a value of the Hubble constant. *[1]*

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(iii) Comment on your answer to (b)(ii). *[2]*

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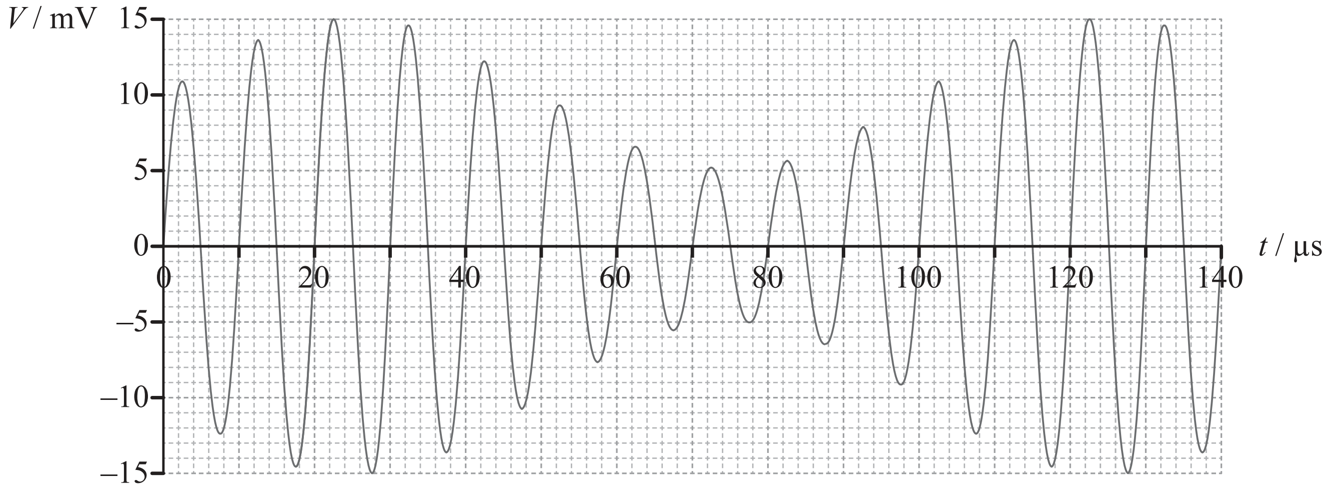
will not be marked.

Option F — Communications

F1. This question is about modulation.

(a) The diagram shows the variation with time of the voltage of an amplitude modulated (AM) carrier wave.



Determine the

(i) frequency of the carrier wave. *[2]*

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(ii) frequency of the signal (information) wave. *[2]*

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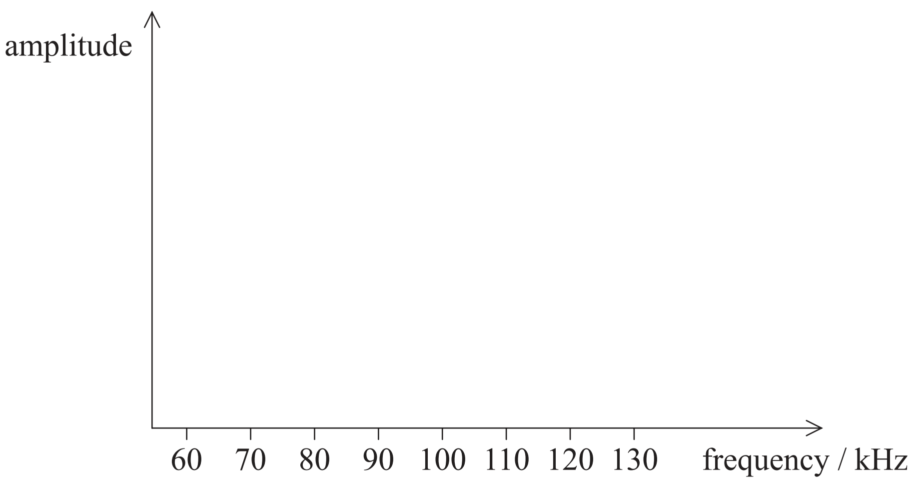
(Question F1 continued)

(iii) bandwidth of the signal. *[1]*

(iv) amplitude of the signal wave. *[2]*

(b) Using the axes below, draw the power spectrum of the modulated carrier wave in (a). *[2]*



F2. This question is about digital transmission.

The sampling frequency in an analogue-to-digital converter (ADC) is 44 kHz.

(a) By reference to the reconstruction of an analogue signal, state and explain the maximum frequency that can be used by this system. *[2]*

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(b) The ADC produces a 32 bit parallel output. Calculate the

(i) bit rate of the transmission. *[1]*

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(ii) duration of one bit. *[1]*

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Answers written on this page
will not be marked.

F3. This question is about attenuation.

(a) For a copper cable, state

(i) what is meant by attenuation. *[1]*

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(ii) **one** cause of attenuation in the copper cable. *[1]*

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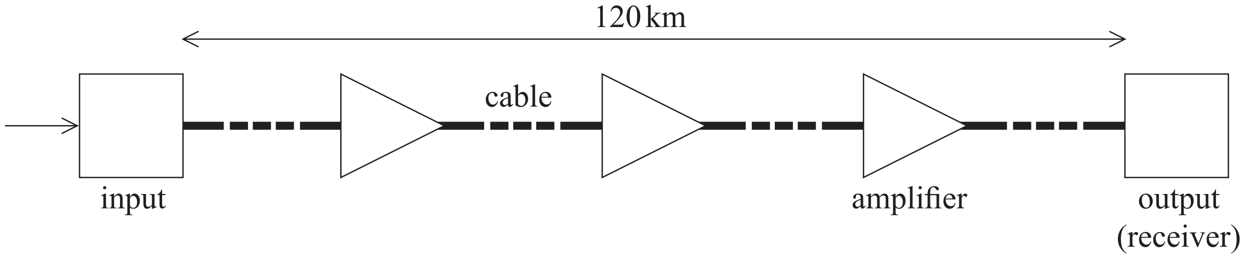
(This question continues on the following page)

(Question F3 continued)

(b) A copper cable of length 120 km is used to transmit a signal. The attenuation per unit length of the cable is 15 dB km^{-1}. Amplifiers, each of gain 52 dB, are placed at equal intervals along the cable.



The power of the input signal is 240 mW. The output signal power must not fall below 12 mW.

(i) Estimate the total number of amplifiers needed. *[4]*

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(ii) State **one** advantage in replacing the cable with an optic fibre. *[1]*

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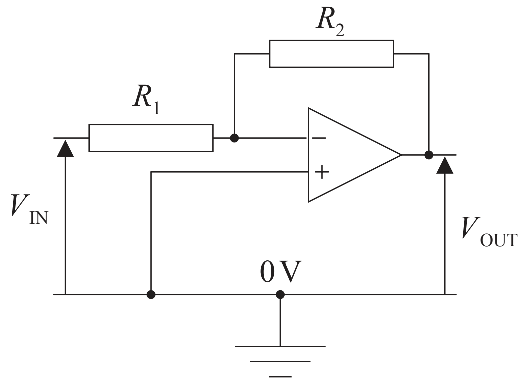
F4. This question is about the operational amplifier (op-amp).

(a) The diagram shows the circuit of an inverting amplifier.



(i) State what is meant by an inverting amplifier. *[1]*

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(ii) On the diagram above, label, with the letter V, the point in the circuit that is referred to as virtual earth. *[1]*

(iii) Show that the gain G of the amplifier is given by the expression $G = -\frac{R_2}{R_1}$. *[3]*

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(This question continues on the following page)

(Question F4 continued)

(b) In the circuit in (a) the resistance of R_1 is 6.0 kΩ and the resistance of R_2 is 60 kΩ. The amplifier operates with a ±12 V supply. Calculate the value of the output voltage V_{OUT} for an input voltage V_{IN} of

(i) 0.30 V. *[1]*

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(ii) 3.0 V. *[1]*

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F5. This question is about the mobile phone system.

A person makes a phone call using a mobile phone. Explain the function of the base stations and the cellular exchange during the phone call. *[3]*

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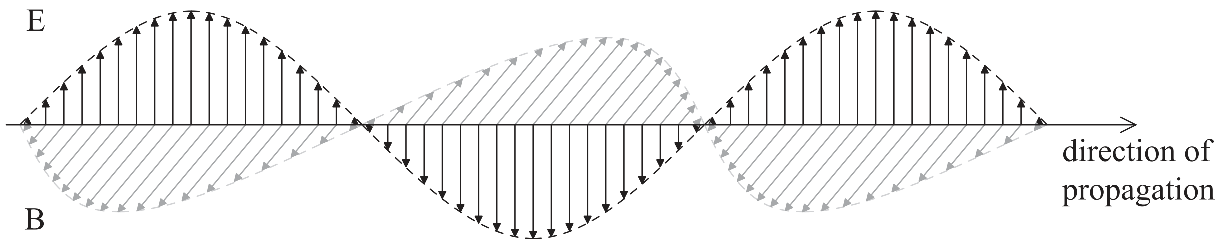
Option G — Electromagnetic waves

G1. This question is about light.

(a) The diagram is a representation of the oscillating electric (E) and magnetic (B) fields in an electromagnetic wave in vacuum. The fields are perpendicular to each other.



(i) State the change, if any, in the angle between E and B when the wave enters a transparent medium from vacuum. *[1]*

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(ii) On the diagram, label a distance that is equal to one wavelength of this electromagnetic wave. *[1]*

(b) State **one** common property of all electromagnetic waves. *[1]*

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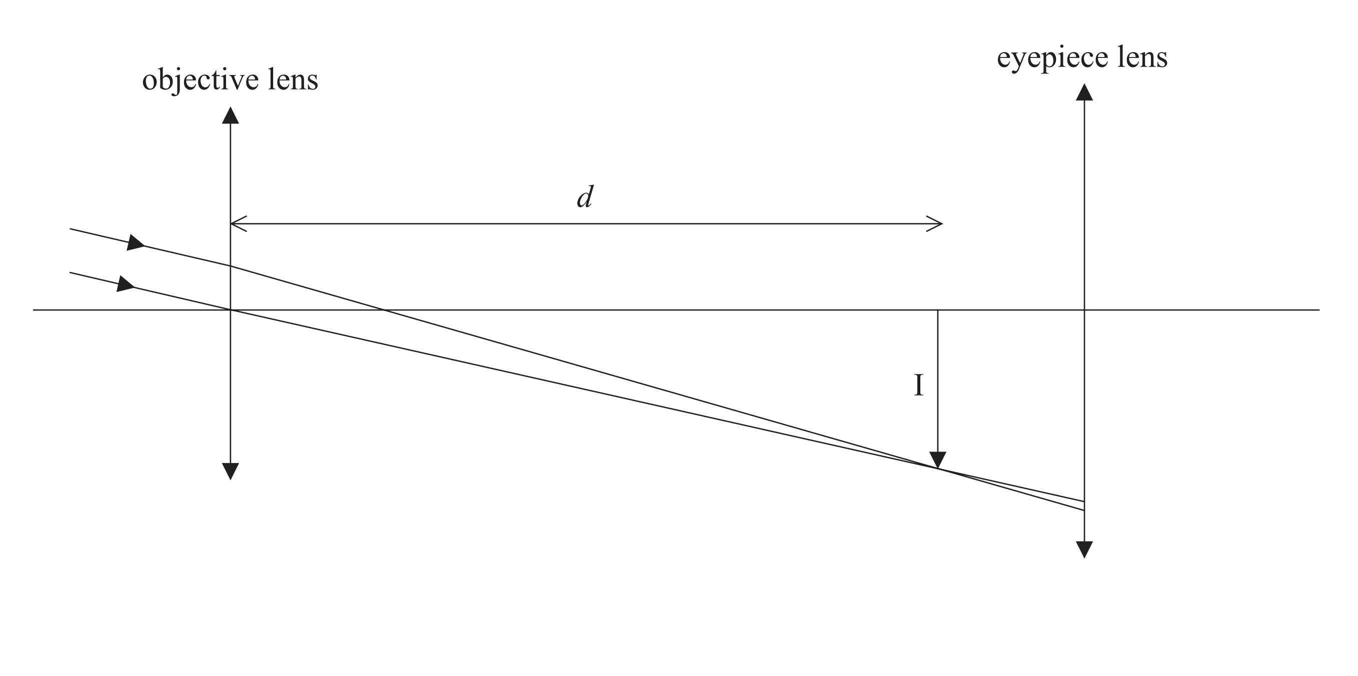
G2. This question is about an astronomical telescope.

(a) The diagram is a partially completed ray diagram for an astronomical telescope.



The image I of a star is formed by the objective lens at a distance *d* from the objective lens. The final image of the star is formed at infinity.

(i) Show that the distance *d* is equal to the focal length of the objective lens. *[2]*

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(ii) On the diagram, label the **two** focal points of the eyepiece lens with the letters F_1 and F_2 respectively. *[1]*

(iii) On the diagram, construct lines to show how the final image of the star is formed at infinity. *[3]*

(iv) The angular magnification of the telescope is defined as $M = \frac{\theta_2}{\theta_1}$. On the diagram, label the angles θ_1 and θ_2. *[1]*

(This question continues on the following page)

(Question G2 continued)

(b) In a particular astronomical telescope in normal adjustment, the focal length of the objective lens is 26 cm and the focal length of the eyepiece lens is 4.0 cm. The telescope is used to view a distant weather balloon whose angular diameter with a naked eye is 2.2°. Determine the angular diameter of the image of the weather balloon formed by the telescope. *[2]*

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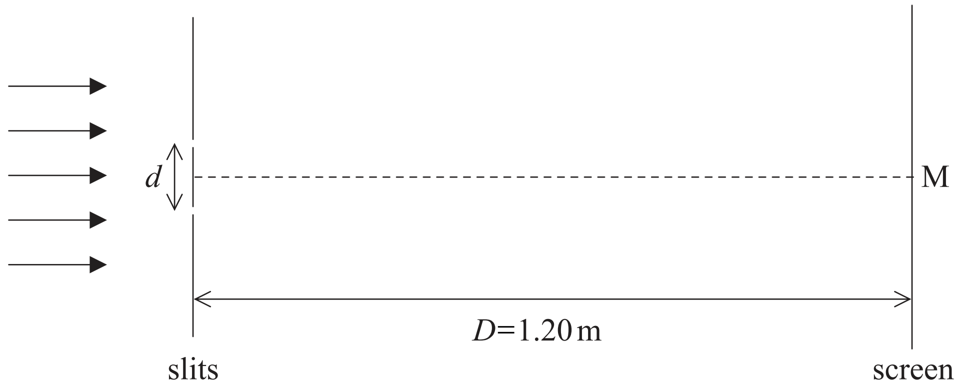
G3. This question is about interference.

(a) Coherent monochromatic light is incident normally on two very narrow, parallel slits whose width is small compared to their separation. After the light passes through the slits it is incident on a screen. The mid-point of the screen is at M.



The distance D between the slits and the screen is 1.20 m. The slit separation d is 0.150 mm.

(i) Explain why the intensity of the light at M is a maximum. *[2]*

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(ii) Point P is the closest point to M on the screen where the light intensity is a minimum. The distance MP is 2.62 mm. Calculate the wavelength of light. *[2]*

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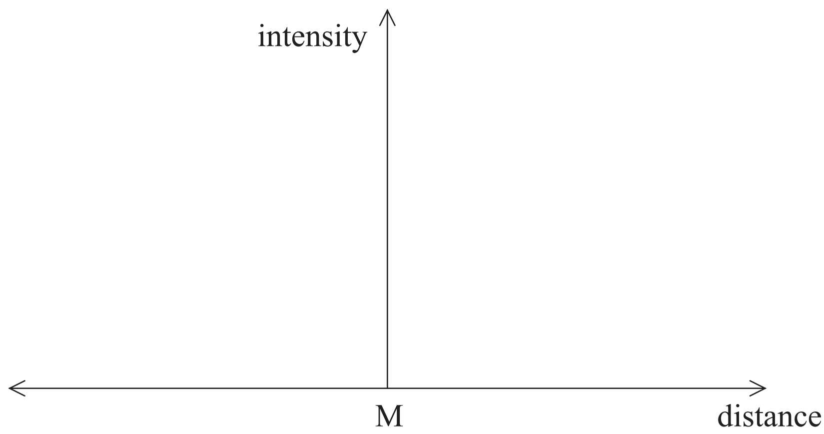
(Question G3 continued)

(b) Using the axes below, sketch a graph to show the variation with distance along the screen of the light intensity. *[2]*



(c) The number of slits is greatly increased, each with the same separation as in (a). Describe the differences, if any, in the intensity distribution in (b). *[2]*

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G4. This question is about X-rays.

(a) (i) An X-ray tube operates at an accelerating voltage of 28 kV. Show that the minimum wavelength λ_{min} of the X-rays produced is 4.4×10^{-11} m. *[2]*

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(ii) State why no X-rays of wavelength less than λ_{min} are produced in this X-ray tube. *[1]*

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(b) X-rays of wavelength $\lambda=4.4\times10^{-11}$ m are incident on a crystal plane. A strong first-order reflected X-ray beam is observed when the X-rays make an angle of 11° with the crystal plane. Calculate the separation of the crystal planes. *[2]*

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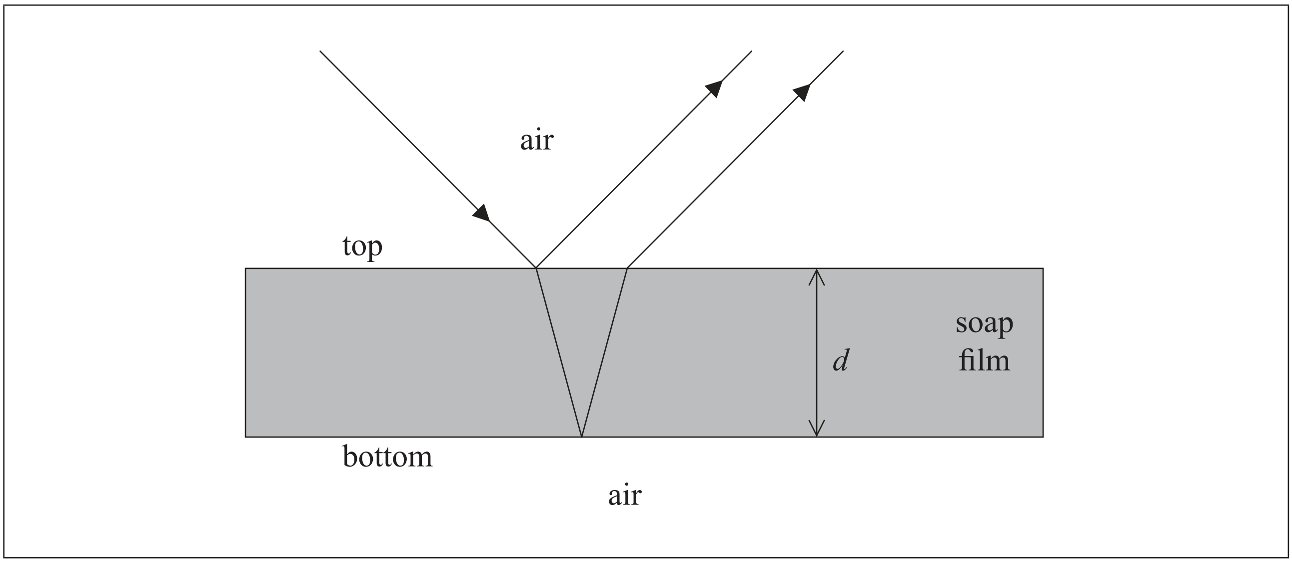
G5. This question is about thin-film interference.

(a) A ray of monochromatic light is incident on a thin film of soap water that is suspended in air. The diagram shows the reflection of this ray from the top and bottom surfaces of the film.



On the diagram, label, with the letter P, the point at which a phase difference of π occurs. *[1]*

(This question continues on the following page)

(Question G5 continued)

(b) White light is incident normally on the soap film. The thickness d of the soap film is 225 nm and its refractive index is 1.34.

(i) Show that the longest wavelength of light λ in air for which the reflected rays destructively interfere is 603 nm. *[2]*

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(ii) Explain why the soap film will appear coloured. *[2]*

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Option H — Relativity

H1. This question is about relativistic kinematics.

(a) Define *proper length*. *[1]*

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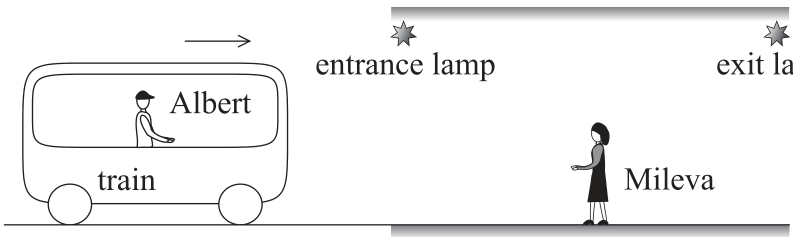
(b) Albert is at rest in a train approaching a tunnel. Mileva is in the tunnel mid-way between the entrance and exit lamps at the ends of the tunnel.



view according to the tunnel observer

The proper length of the train is 120 m and the proper length of the tunnel is 72 m. The train moves with speed 0.80c relative to the tunnel. Calculate the

(i) gamma factor for a speed of 0.80c. *[1]*

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(ii) length of the train according to Mileva. *[1]*

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(This question continues on the following page)

(Question H1 continued)

(iii) length of the tunnel according to Albert. *[1]*

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(c) The lamps in the tunnel are switched on. According to Mileva the lamps switch on simultaneously. Explain why, according to Albert, the entrance lamp switches on after the exit lamp. *[3]*

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(Question H1 continued)

(d) The diagrams below show two events. In event 1 the train in (b) is about to exit the tunnel and in event 2 the train has just exited the tunnel. The proper length of the train is 120 m and the proper length of the tunnel is 72 m.

Determine the time between these two events according to

(i) Mileva. *[1]*

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(ii) Albert. *[2]*

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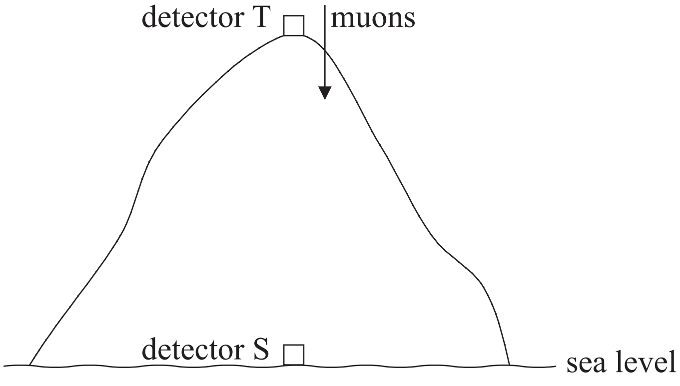
H2. This question is about muon decay experiments.

Muons created high in the atmosphere move vertically down towards the surface of Earth. A muon detector T is placed on top of a mountain and another, detector S, is placed at sea level.



Detector T detects 570 muons per hour. In the rest frame of the muons their half-life is 1.5 μs. According to an observer, at rest on the mountain, the muons take 6.0 μs to travel from detector T to detector S.

(a) Show that, if the muons move at non-relativistic speed, the number of muons detected at sea level would be approximately 36 per hour. *[2]*

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(This question continues on the following page)

(Question H2 continued)

(b) The muons in (a) move toward the surface of Earth with a relativistic speed of 0.968c.

(i) Determine the half-life of the muons according to the observer at rest on the mountain. *[2]*

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(ii) The number of muons observed at detector S is 285 per hour. Explain, using your answers to (a) and (b)(i), how this observation provides evidence for time dilation. *[2]*

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H3. This question is about relativistic mechanics.

A proton, after acceleration from rest through a potential difference *V*, has momentum $1600\ \text{MeV}\ c^{-1}$.

(a) Calculate the value of *V*. *[3]*

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(b) Calculate the speed of the proton after acceleration. *[2]*

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H4. This question is about general relativity.

(a) State the equivalence principle. *[1]*

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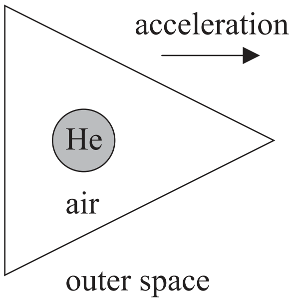
(b) A helium filled balloon is floating in air inside a spacecraft in outer space. The spacecraft begins to accelerate to the right.



Explain, with reference to the equivalence principle, the motion, if any, of the helium balloon relative to the spacecraft. *[3]*

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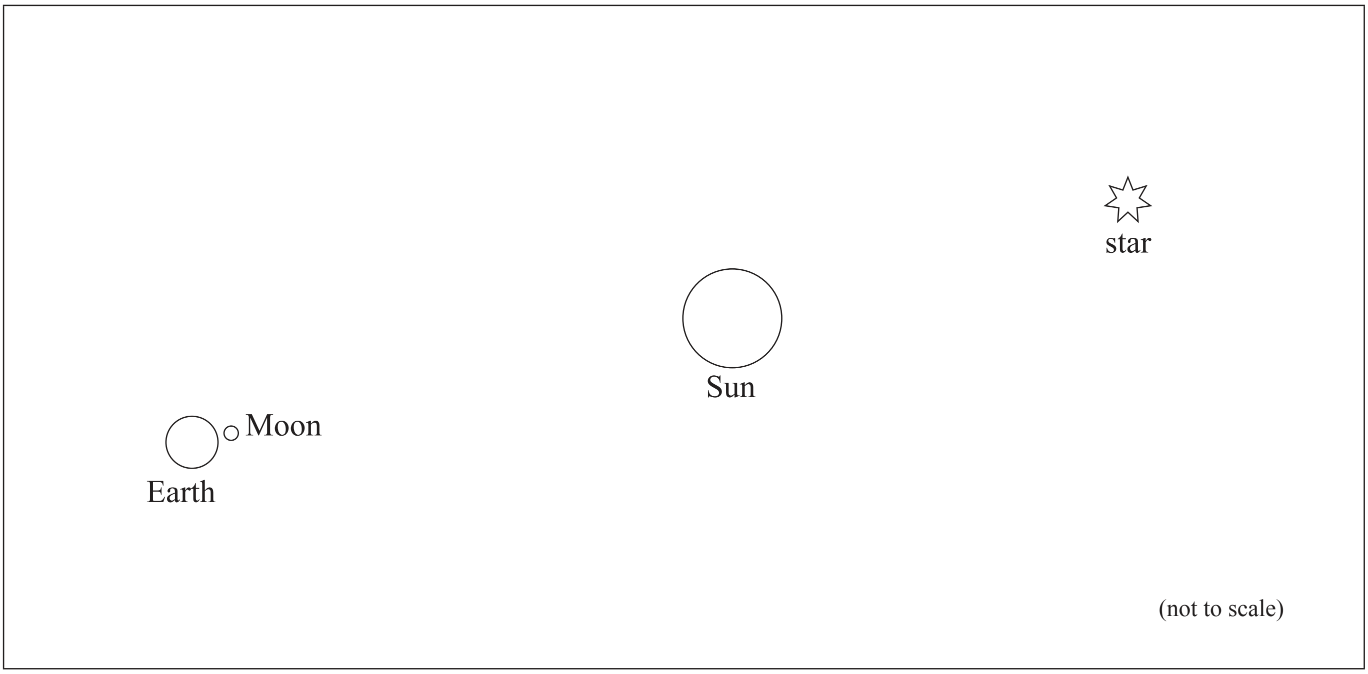
(Question H4 continued)

(c) In an experiment, to verify the bending of light as it passes close to the Sun, the position of a star was measured during a total solar eclipse.



(i) Explain why the measurement of the star's position was made during a total solar eclipse. *[1]*

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(ii) On the diagram above, draw lines to determine the apparent position of the star as seen from Earth. *[1]*

(iii) State what other measurement must be made in order to determine the angle by which rays from the star are bent by the Sun. *[1]*

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(This question continues on the following page)

(Question H4 continued)

(iv) The angle of bending of a light ray from the star that just grazes the Sun's surface is θ. State and explain the effect, if any, on θ if the Sun were to be replaced by another star of equal radius but larger mass. *[2]*

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Option I — Medical physics

I1. This question is about hearing.

(a) Define *sound intensity level*. *[1]*

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(b) A student stands at a distance of 12 m from a rock band in a concert. The sound intensity level at the student's ear is 105 dB. The area of the student's eardrum is 58 mm^2.

(i) Show that the power incident on the student's eardrum is 1.8 μW. *[2]*

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(ii) Calculate the distance from the band at which the student must stand so that the sound intensity level is reduced to 90 dB. *[3]*

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I2. This question is about X-rays.

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

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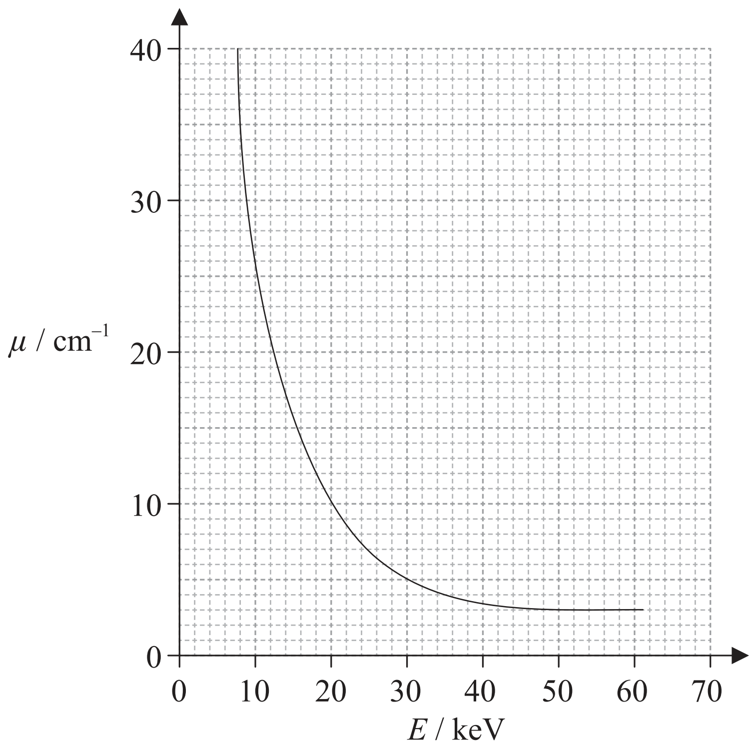
(b) The graph shows how the attenuation coefficient μ of muscle varies with photon energy E.



In X-ray imaging, photons of energy less than 20 keV are filtered out of the beam.

(This question continues on the following page)

(Question I2 continued)

(i) Explain, with reference to the graph, why this does not significantly affect the quality of the X-ray image produced. *[2]*

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(ii) State the advantage to the patient of filtering out the low energy photons from the X-ray beam. *[1]*

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(iii) Calculate the fraction of the intensity transmitted through 3.0 mm of muscle for X-rays of energy 50 keV. *[2]*

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I3. This question is about nuclear magnetic resonance (NMR) imaging.

(a) Outline the physical principles of NMR imaging. *[5]*

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(b) State **two** advantages of NMR imaging over computed tomography (CT) imaging. *[2]*

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will not be marked.

I4. This question is about radiation and dosimetry.

(a) Suggest why it is desirable for a radio-isotope to be a gamma emitter if it is to be used for diagnostic purposes. *[2]*

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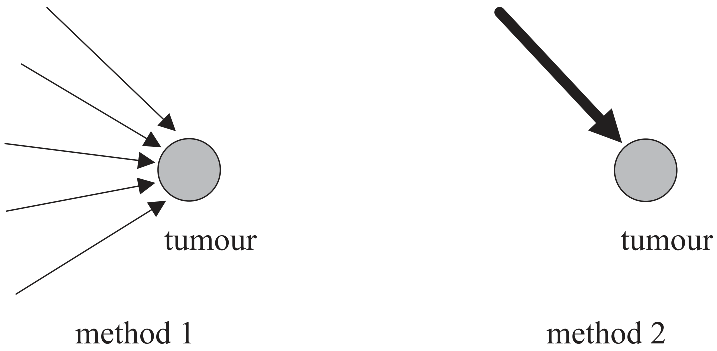
(b) Two methods of radiation therapy involve gamma rays. In method 1 the tumour is irradiated with many fine beams from many different directions. In method 2 the tumour is irradiated by a single beam of the same total energy as the beams in method 1.



Suggest and explain an advantage to the patient of method 1 over method 2. *[2]*

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(Question I4 continued)

(c) A patient is injected with a quantity of technetium-99^{m}. Technetium decays by gamma photon emission. The physical half-life of technetium is 6.0 hours and its biological half-life is 60 hours.

(i) Distinguish between physical and biological half-life. *[2]*

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(ii) Show that the effective half-life of technetium is 5.5 hours. *[1]*

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(iii) The following data are available for a patient injected with technetium.

Mass of patient	= 72 kg
Average activity of technetium	= 350 MBq
Energy of each of the photons emitted	= 140 keV
Quality factor for gamma radiation	= 1

Determine the dose equivalent received by the patient in 5.5 hours. *[4]*

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Option J — Particle physics

J1. This question is about quarks and interactions.

(a) Distinguish between the quark structure of a baryon and a meson. *[1]*

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(b) Calculate the magnitude of the smallest non-zero spin that a particle can have. *[1]*

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(c) (i) State the Pauli exclusion principle. *[1]*

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(ii) The hadron Δ^{++} consists of three u quarks and has spin $\frac{3}{2}$.

Explain how it is possible for the quarks in Δ^{++} not to violate the Pauli principle. *[2]*

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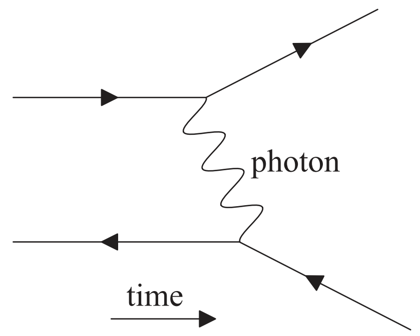
(Question J1 continued)

(d) The Feynman diagram represents the electromagnetic scattering of an electron and a positron.



(i) Identify a positron on the diagram by labelling it with e^+. *[1]*

(ii) State and explain the range of the interaction. *[2]*

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(e) The following reactions have never been observed. For each reaction state **one** conservation law that would be violated if the reactions were to occur. *[2]*

$e^+ + e^+ \rightarrow p^+ + p^+$ . . . .

$e^- + \nu \rightarrow e^+ + \overline{\nu}$ . . . .

J2. This question is about particle production.

(a) In a particular experiment, moving kaon mesons collide with stationary protons. The following reaction takes place

$$p + K^{-} \rightarrow K^{0} + K^{+} + \mathrm{X}$$

where X is an unknown particle. This process involves the strong interaction. The quark structure of the kaons is $K^{-} = \bar{u}s$, $K^{0} = d\bar{s}$, and $K^{+} = u\bar{s}$.

(i) State the strangeness of the unknown particle X. *[1]*

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(ii) Particle X is a hadron. State and explain whether X is a meson **or** a baryon. *[2]*

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(Question J2 continued)

(b) The masses of the particles involved in the reaction are as follows.

$$\begin{aligned} p &= 938\,\text{MeV}\,\text{c}^{-2} \\ K^{-} &= 494\,\text{MeV}\,\text{c}^{-2} \\ K^{0} &= 498\,\text{MeV}\,\text{c}^{-2} \\ K^{+} &= 494\,\text{MeV}\,\text{c}^{-2} \end{aligned}$$

For the reaction to take place, the K^{-} must be accelerated to a minimum total energy E of approximately 3170 MeV. Determine the mass of particle X. *[4]*

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(c) Particles produced by collisions such as that in (a) may be detected using a wire chamber. Outline the operation of a wire chamber. *[3]*

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J3. This question is about the standard model of particles.

(a) Outline what is meant by asymptotic freedom. *[2]*

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(b) Describe the experimental evidence for asymptotic freedom. *[2]*

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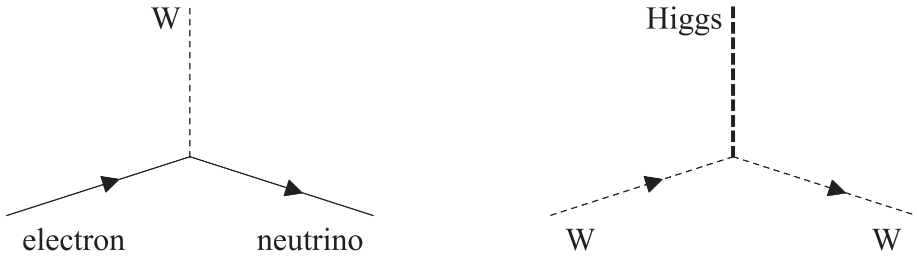
(Question J3 continued)

(c) The following two diagrams represent weak interaction vertices involving the postulated Higgs boson.



The Higgs and W bosons are unstable particles. Use the interaction vertices to construct a Feynman diagram for the decay of a Higgs boson into stable particles. *[2]*

J4. This question is about the early universe.

(a) Determine the temperature at which thermal fluctuations could create an electron-positron pair out of a vacuum. *[2]*

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(b) Electron-positron pairs are produced at temperatures less than that in the answer to (a). Explain this observation. *[2]*

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