N10/4/PHYSI/HP3/ENG/TZ0/XX

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PHYSICS
HIGHER LEVEL
PAPER 3

Tuesday 9 November 2010 (morning)

1 hour 15 minutes

Candidate session number

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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 in the spaces provided.
- At the end of the examination, indicate the letters of the Options answered in the candidate box on your cover sheet.

Option E — Astrophysics

E1. This question is about the characteristics of the stars Procyon A and Procyon B.

(a) The stars Procyon A and Procyon B are both located in the same stellar cluster in the constellation Canis Minor. Distinguish between a constellation and a stellar cluster. *[2]*

Constellation: . . . .

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Stellar cluster: . . . .

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(b) The table shows some data for Procyon A and Procyon B.

	Apparent magnitude	**Absolute magnitude**	**Apparent brightness / $W\,m^{-2}$**
Procyon A (P_A)	+0.400	+2.68	2.06×10^{-8}
Procyon B (P_B)	+10.7	+13.0	1.46×10^{-12}

Explain, using data from the table, why

(i) as viewed from Earth, P_A is much brighter than P_B. *[2]*

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(ii) the luminosity of P_A is much greater than that of P_B. *[3]*

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(This question continues on the following page)

(Question E1 continued)

(c) Deduce, using data from the table in (b), that P_A and P_B are approximately the same distance from Earth. *[2]*

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(d) State, using your answers to (a) and (c), why P_A and P_B might be binary stars. *[1]*

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(e) Calculate, using data from the table in (b), the ratio $\frac{L_A}{L_B}$ where L_A is the luminosity of P_A and L_B is the luminosity of P_B. *[2]*

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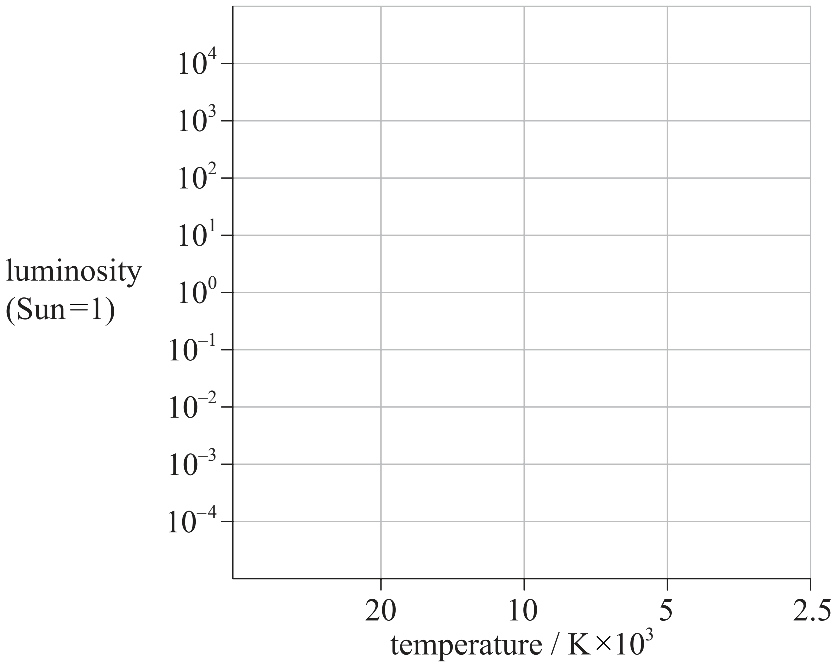
(This question continues on the following page)

(Question E1 continued)

(f) The surface temperature of both P_A and P_B is of the order of 10^4 K. The luminosity of P_A is of the order of $10L_S$, where L_S is the luminosity of the Sun. The diagram shows the grid of a Hertzsprung–Russell diagram.



Label, on the grid above, the approximate position of

(i) star P_A with the letter A. *[1]*

(ii) star P_B with the letter B. *[1]*

(g) Identify the nature of star P_B. *[1]*

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(h) On the grid provided in (f), draw the evolutionary path of the star P_A. *[2]*

(This question continues on the following page)

(Question E1 continued)

(i) The luminosity of the main sequence star Regulus is $150\,L_S$. Assuming that, in the mass–luminosity relationship, $n = 3.5$ show that the mass of Regulus is $4.2\,M_S$ where M_S is the mass of the Sun. *[2]*

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(j) The star Betelgeuse is about five times the mass of Regulus. One possible outcome of the final stage of the evolution of Betelgeuse is for it to become a black hole. State the

(i) other possible outcome of the final stage of the evolution of Betelgeuse. *[1]*

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(ii) reason why the final stage in (j)(i) is stable. *[1]*

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E2. This question is about the Big Bang model and red-shift.

(a) Describe what is meant by the Big Bang model. *[1]*

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(b) In the 1960s, Penzias and Wilson discovered a uniform cosmic background radiation (CMB) in the microwave region of the electromagnetic spectrum.

(i) Explain how the CMB is consistent with the Big Bang model. *[3]*

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(ii) State why the red-shift of light from galaxies supports the Big Bang model. *[1]*

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(c) Many galaxies are a great distance from Earth. Explain, with reference to Hubble's law, how the measurement of the red-shift of light from such galaxies enables their distance from Earth to be determined. *[3]*

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(d) State **one** problem associated with using Hubble's law to determine the distance of a galaxy a great distance from Earth. *[1]*

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Option F — Communications

F1. This question is about modulation.

(a) State what is meant by the modulation of a carrier wave. *[1]*

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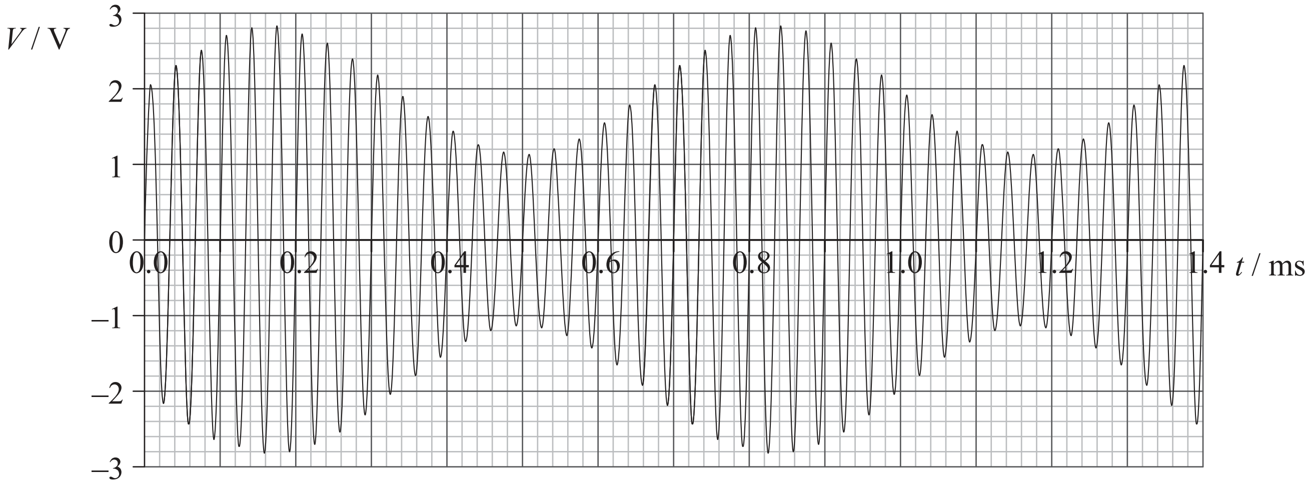
(Question F1 continued)

(b) The graph shows how the voltage signal strength V of an amplitude modulated (AM) carrier wave varies with time t.



Use the graph to determine the

(i) frequency of the carrier wave. *[1]*

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(ii) frequency of the signal wave. *[1]*

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

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(iv) bandwidth. *[1]*

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(c) A carrier wave may also be frequency modulated (FM). State and explain **one** advantage of FM compared to AM. *[2]*

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F2. This question is about optical fibres.

(a) Outline what is meant by material dispersion. *[2]*

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(b) Suggest why material dispersion sets a limit on the bit-rate of transmission. *[1]*

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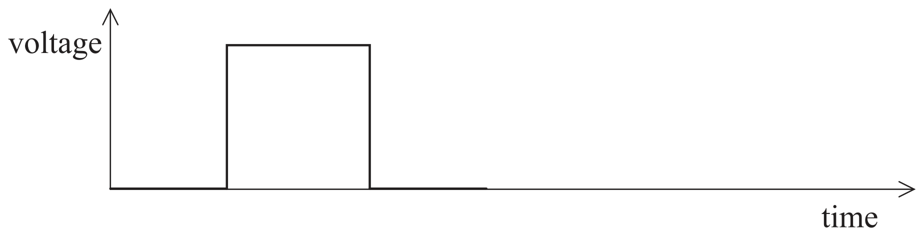
(c) (i) The signal shown below is fed into a monomode optical fibre.



On the diagram above, show the effects of material dispersion on the input signal by drawing the shape of the signal after it has travelled a long distance in the optical fibre. *[1]*

(ii) State and explain how the effects on the signal drawn in (c)(i) may be reduced. *[2]*

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(This question continues on the following page)

(Question F2 continued)

(d) Digital data are transmitted in an optical fibre with a glass core which has a refractive index of 1.5. The duration of one bit in the transmission is 0.50 ns and each sample in the signal consists of 32 bits.

(i) Calculate the time required for the signal to travel a distance of 500 km. *[2]*

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(ii) Determine the sampling frequency. *[2]*

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(e) The data in (d) are confidential and must be protected. Without taking financial costs into account, outline whether a direct optical fibre connection **or** a transmission through a geosynchronous satellite would be more suitable for the transfer of these data. *[2]*

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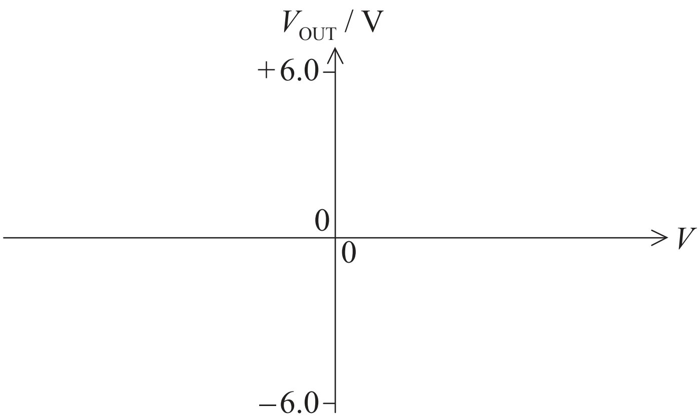
F3. This question is about an operational amplifier used in a Schmitt trigger circuit.

(a) An operational amplifier uses a ±6.0 V supply. The operational amplifier operates in the non-inverting mode.

(i) On the axes below, sketch a graph to show how the output voltage V_{OUT} of the amplifier varies with the potential difference V between the two inputs of the amplifier. *[2]*



(ii) With reference to the graph sketched in (a)(i), explain why the operational amplifier is said to act as a comparator. *[2]*

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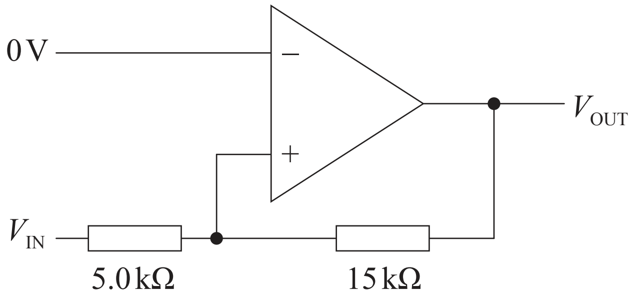
(Question F3 continued)

(b) The diagram shows an operational amplifier connected as a Schmitt trigger. The output of the amplifier is ±6.0 V.



(i) Show that the upper switching voltage of the trigger, *i.e.* the input voltage V_{IN} for which the output voltage V_{OUT} switches from –6.0 V to +6.0 V, is 2.0 V. *[2]*

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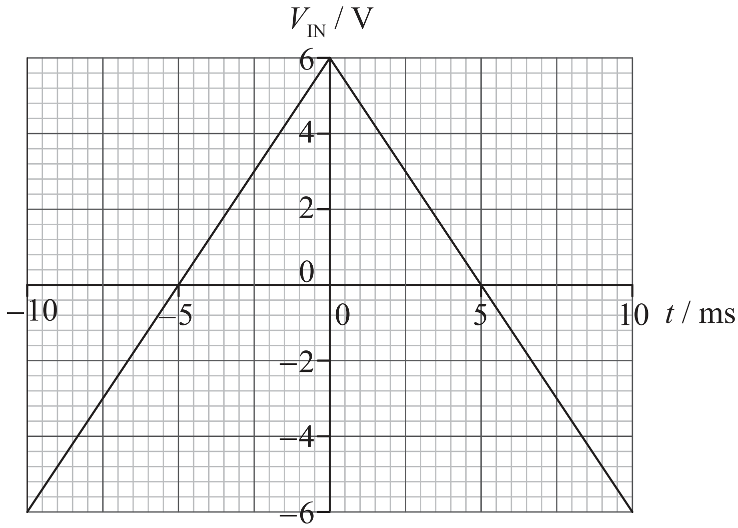
(Question F3 continued)

(ii) The input signal V_{IN} to the trigger is shown in the graph.



The switching voltages of the trigger are ±2.0 V.

On the axes above, sketch a graph to show how the output voltage V_{OUT} varies with time t. *[2]*

(c) Explain the use of a Schmitt trigger in the transmission of digital signals. *[2]*

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Option G — Electromagnetic waves

G1. This question is about lasers.

(a) With reference to the light waves emitted by a laser, state what is meant by the terms

(i) monochromatic. *[1]*

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(ii) coherent. *[1]*

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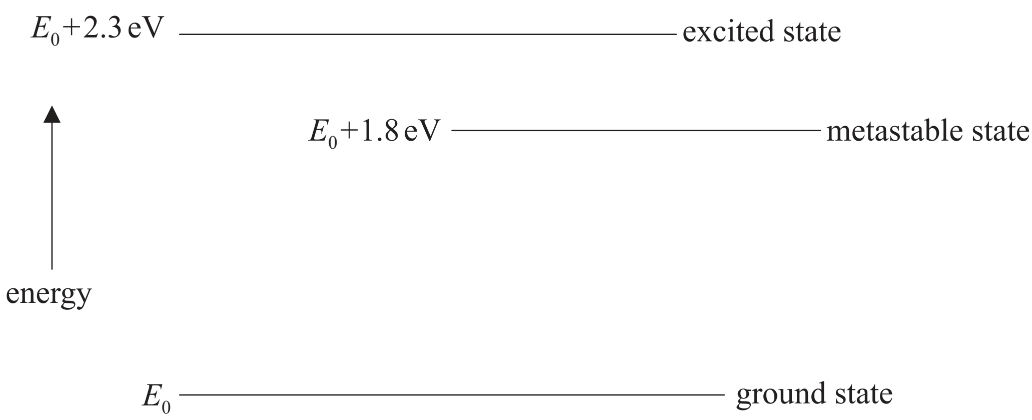
(Question G1 continued)

(b) The diagram (not to scale) shows three of the energy levels of a substance used to produce laser light.



The energy of the ground state is E_0.

(i) State what is meant by population inversion. *[1]*

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(ii) Draw an arrow on the diagram to indicate the transition that results in a population inversion. Label the arrow P. *[1]*

(iii) Draw an arrow on the diagram to indicate the transition that results in a pulse of laser light. Label the arrow L. *[1]*

(iv) Deduce that the wavelength of the emitted laser light is 690 nm. *[1]*

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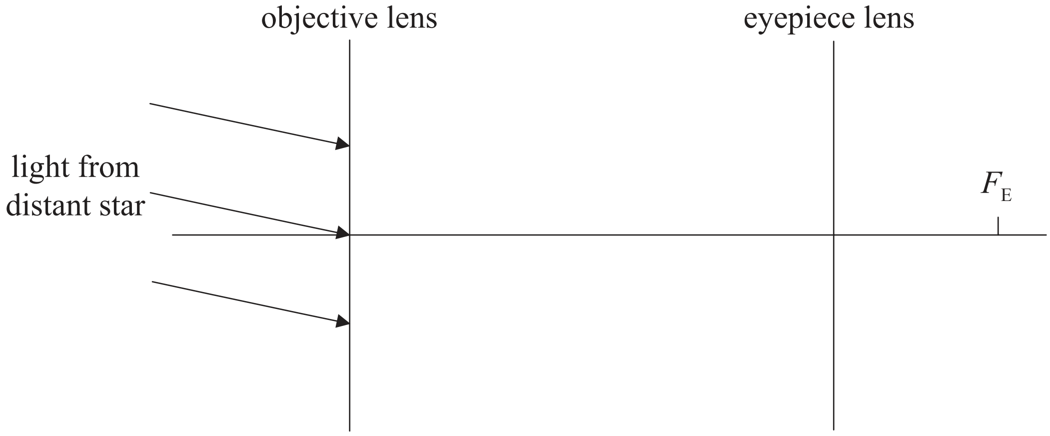
G2. This question is about an astronomical telescope.

The diagram (not to scale) shows the arrangement of the two convex lenses in an astronomical telescope in normal adjustment.



The telescope is used to observe a distant star. One of the focal points of the eyepiece lens is labelled F_E.

(a) On the diagram above,

(i) label, with the symbol F_E, the position of the other focal point of the eyepiece lens. *[1]*

(ii) label, with the symbol F_O, the position of the focal point of the objective lens that is in between the two lenses. *[1]*

(iii) construct rays to locate the final image of the star. *[3]*

(b) In a particular astronomical telescope, the eyepiece lens has a power of 40 dioptres and the objective lens a power of 0.80 dioptres. Determine the angular magnification of the telescope in normal adjustment. *[2]*

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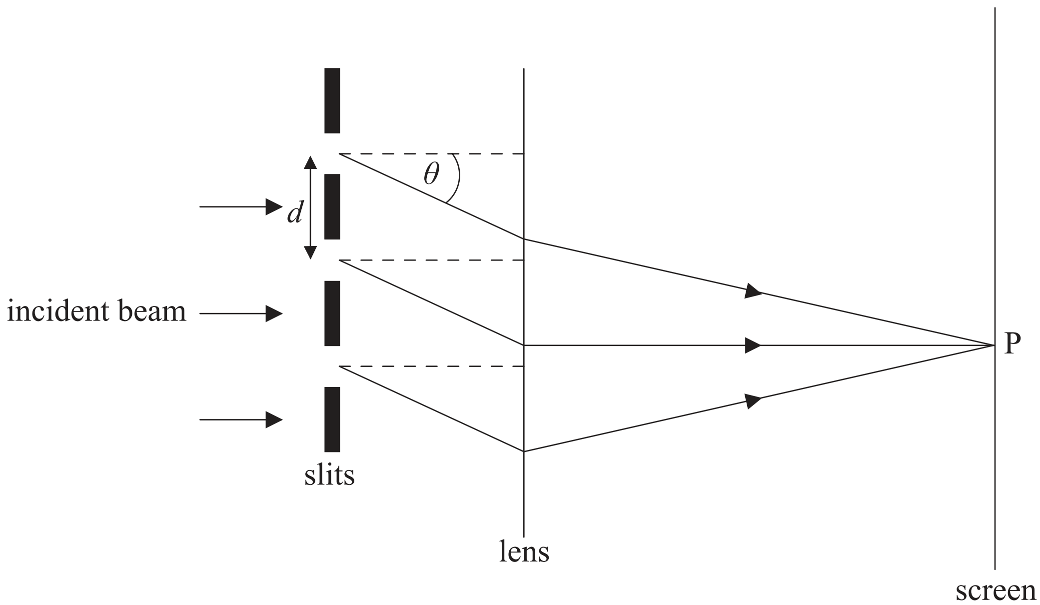
(c) In an astronomical telescope the objective is often made up from a diverging and a converging lens, whereas the aperture of the eyepiece lens is usually restricted such that only rays close to the principal axis are viewed. State the reasons for this. *[2]*

Objective lens: . . . .

Eyepiece lens: . . . .

G3. This question is about a diffraction grating.

(a) A parallel beam of monochromatic light is incident normally on a diffraction grating. After passing through the grating it is brought to a focus on a screen by a lens. The diagram shows a few of the slits of the diffraction grating and the path of the light that is diffracted at an angle θ to each slit.



The distance between the slits is d and the wavelength of the light is λ.

(i) On the diagram, construct a line that enables the path difference between the rays from two adjacent slits to be shown. Label the path distance L. *[1]*

(ii) Use your answer to (a)(i) to derive the condition, in terms of d and θ, for there to be a maximum of intensity at the point P on the screen. *[2]*

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(b) For a particular grating, the distance between adjacent slits is 2.0×10^{-6} m. Determine, for light of wavelength 520 nm, the maximum theoretical order of diffraction. *[2]*

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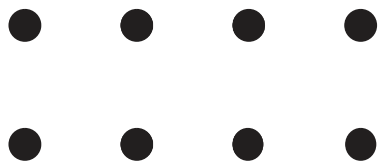
G4. This question is about X-ray diffraction.

(a) The diagram represents some of the atoms in two layers of a cubic crystal lattice.



Use the diagram to outline how diffraction arises from the scattering of X-rays by a crystal. *[3]*

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(b) X-rays of wavelength 87 pm are scattered by a crystal whose atoms are arranged in a cubic lattice. The smallest scattering angle for which a maximum of the scattered X-ray is observed is 18°. Calculate the spacing between adjacent atoms in the crystal. *[2]*

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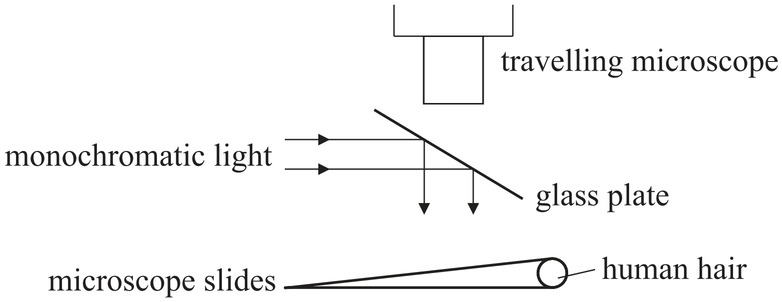
G5. This question is about thin-film interference.

The diagram (not to scale) represents an experimental set-up designed to measure the diameter of a human hair.



A hair is used to separate two microscope slides. A monochromatic beam of light is reflected onto the two slides by the glass plate. The light is then reflected from the two slides and transmitted through the glass plate and is viewed by the travelling microscope.

(a) State why the light reflected from the two microscope slides produces a system of interference fringes. *[1]*

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(b) The condition that a bright fringe is observed in the field of view of the travelling microscope is given by the relationship

$$2t = \left(m + \tfrac{1}{2}\right)\lambda$$

where t is the thickness of the air film formed by the wedge at the point where the bright fringe is observed, m is an integer and λ is the wavelength of the incident light.

State the reason for the factor $\frac{1}{2}$ in the relationship. *[1]*

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(c) In the diagram, the length of the slides is 5.00 cm. The wavelength of the monochromatic light is 5.92×10^{-7} m. Using the travelling microscope it is observed that 50 fringes occupy a length of 0.940 cm. Show that the diameter of the hair used to separate the slides is about 80 μm. *[3]*

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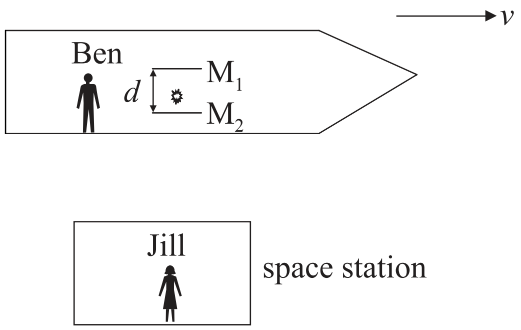
Option H — Relativity

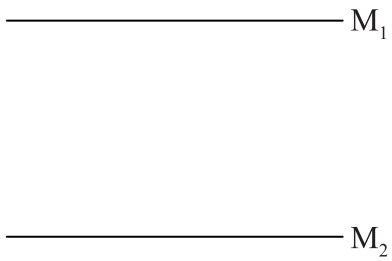
H1. This question is about a Galilean transformation and time dilation.

Ben is in a spaceship that is travelling in a straight-line with constant speed v as measured by Jill who is in a space station.



Ben switches on a light pulse that bounces vertically (as observed by Ben) between two horizontal mirrors M_1 and M_2 separated by a distance d. At the instant that the mirrors are opposite Jill, the pulse is just leaving the mirror M_2. The speed of light in air is c.

(a) On the diagram, sketch the path of the light pulse between M_1 and M_2 as observed by Jill. *[1]*



(b) The time for the pulse to travel from M_2 to M_1 as measured by Jill is Δt.

(i) State, according to Jill, the distance moved by the spaceship in time Δt. *[1]*

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(ii) Using a Galilean transformation, derive an expression for the length of the path of the light between M_2 and M_1. *[2]*

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(This question continues on the following page)

(Question H1 continued)

(c) State, according to special relativity, the length of the path of the light between M_2 and M_1 as measured by Jill in terms of c and Δt. *[1]*

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(d) The time for the pulse to travel from M_2 to M_1 as measured by Ben is $\Delta t'$. Use your answer to (b)(i) and (c) to derive a relationship between Δt and $\Delta t'$. *[3]*

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(e) According to a clock at rest with respect to Jill, a clock in the spaceship runs slow by a factor of 2.3. Show that the speed v of the spaceship is 0.90c. *[2]*

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(f) The length of a table in the spaceship is measured by Ben to be 1.8 m. Calculate the length of the table as measured by Jill. *[1]*

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(g) The questions (e) and (f) introduce the concepts of time dilation and length contraction. Discuss how muon decay in the atmosphere provides experimental evidence for these concepts. *[5]*

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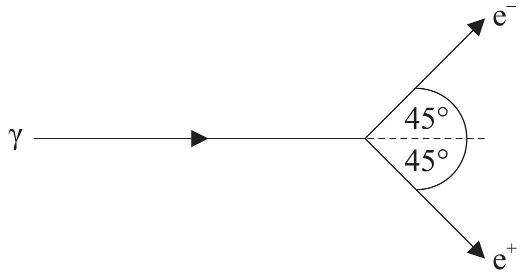
H2. This question is about pair production and relativistic mechanics.

A γ-photon of energy 2.46 MeV is travelling close to the nucleus of a gold atom. It converts into an electron (e^-) – positron (e^+) pair. Each particle travels at 45° to the original direction of the photon.



Immediately after the conversion, the kinetic energies of the electron and positron are equal. The magnitude of the recoil momentum of the gold nucleus is 0.880 MeV c^{-1} and is in the direction of the photon.

(a) Calculate, immediately after the decay, the magnitude of the momentum of the electron. *[4]*

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(b) Calculate the value V of the potential difference through which an electron at rest must be accelerated in order to have the same magnitude of momentum as that in (a). *[2]*

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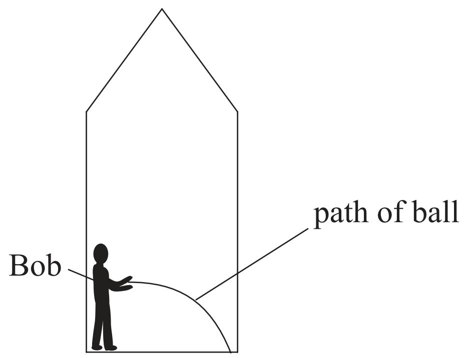
H3. This question is about general relativity.

Bob is standing on the floor of a spaceship and he throws a ball in a direction parallel to the floor.



Between leaving Bob's hand and landing on the floor, the ball follows the path shown.

(a) State and explain whether, from the path followed by the ball, Bob can deduce that the spaceship is at rest on the surface of a planet. *[3]*

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(b) Outline how the concept of spacetime can be used to explain the

(i) trajectory of the ball if the spaceship is at rest on the surface of a planet. *[2]*

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(ii) nature of a black hole. *[2]*

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(This question continues on the following page)

(Question H3 continued)

(c) Calculate the radius that Earth would have to have in order for it to behave as a black hole. The mass of Earth is 6.0×10^{24} kg. *[1]*

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Option I — Medical physics

I1. This question is about sound intensity.

(a) Define

(i) *intensity of sound*. *[1]*

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(ii) *sound intensity level*. *[1]*

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(b) State **two** ways by which the sound pressure at the ear drum is amplified before reaching the cochlear fluid. *[2]*

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(c) A student with a hearing problem can hear sounds clearly when the sound intensity level is 65 dB or higher. In a large lecture hall, at a distance of 25 m from the lecturer, the sound intensity level is 55 dB.

Determine the maximum distance from the lecturer at which the student can hear clearly. The intensity of sound a distance d from a source of power P is given by $I = \frac{P}{4\pi d^2}$. *[4]*

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I2. This question is about X-rays.

(a) Define *half-value thickness*. *[1]*

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(b) The half-value thickness in tissue for X-rays of a specific energy is 3.50 mm. Determine the fraction of the incident intensity of X-rays that has been transmitted through tissue of thickness 6.00 mm. *[3]*

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(c) For X-rays of higher energy than those in (b), the half-value thickness is greater than 3.50 mm. State and explain the effect, if any, of this change on your answer in (b). *[2]*

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(d) X-ray images are often blurred despite the patient remaining stationary during exposure.

(i) State **one** possible physical mechanism for the blurring of an X-ray image. *[1]*

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(ii) For the physical mechanism stated in (d)(i) suggest how X-ray images can be made more distinct. *[2]*

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(This question continues on the following page)

(Question I2 continued)

(e) The exposure time of photographic film to X-rays is longer than that for visible light. The exposure time for X-rays may be reduced with the use of enhancement techniques, such as that of an intensifying screen. Outline how an intensifying screen reduces the exposure time. *[2]*

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I3. This question is about lasers in medicine.

In a procedure called pulse oximetry, lasers are used to measure the percentage of oxygen in the blood. Outline how lasers are used in this procedure. *[3]*

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I4. This question is about dosimetry.

(a) Distinguish between the terms absorbed dose and dose equivalent. *[2]*

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(b) A beta source is injected into a tumour in a patient. The following data are available.

Mass of tumour	$= 65\,\text{g}$
Activity of source	$= 4.8 \times 10^8\,\text{Bq}$
Average energy of emitted electrons	$= 1.2\,\text{MeV}$
Quality factor of beta radiation	$= 1.0$

(i) Determine the dose equivalent over a period of fifteen minutes after the beta source is injected into the tumour. *[4]*

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(ii) State **one** reason why the dose equivalent determined in (b)(i) is only approximate. *[1]*

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(iii) State **one** reason why patients might be willing to subject themselves to such a considerable amount of radiation as determined in (b)(i). *[1]*

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Option J — Particle physics

J1. This question is about leptons and mesons.

(a) Leptons are a class of elementary particles and each lepton has its own antiparticle. State what is meant by an

(i) elementary particle. *[1]*

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(ii) antiparticle of a lepton. *[1]*

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(b) The electron is a lepton and its antiparticle is the positron. The following reaction can take place between an electron and positron.

$$e^- + e^+ \rightarrow \gamma + \gamma$$

Sketch the Feynman diagram for this reaction and identify on your diagram any virtual particles. *[3]*

(This question continues on the following page)

(Question J1 continued)

(c) Unlike leptons, the π^+ meson is not an elementary particle. State the

(i) quark structure of the π^+ meson. *[1]*

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(ii) reason why the following reaction does not occur. *[1]*

$$p^+ + p^+ \rightarrow p^+ + \pi^+$$

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

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(e) Explain, with reference to your answer to (d), why quarks are assigned the property of colour. *[2]*

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(f) The pion was suggested to be the mediating particle of the strong interaction between nucleons. Given that the range of the strong nuclear interaction between nucleons is about 10^{-15} m, show that the rest mass of the pion is about 100 MeV c^{-2}. *[3]*

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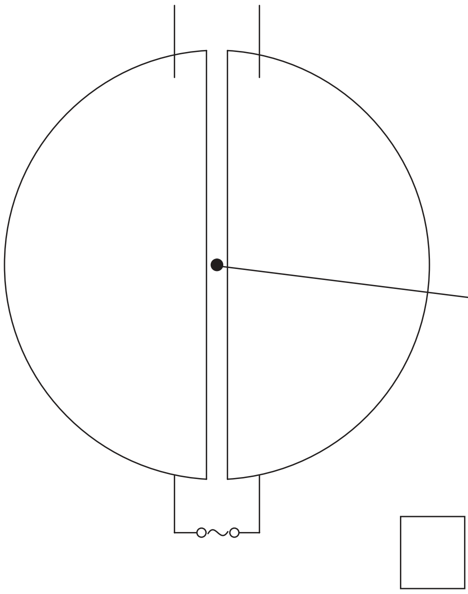
J2. This question is about particle accelerators.

(a) The diagram (not to scale) represents a view from above of the essential features of a cyclotron.



The positive particles emitted by the source, travel in an anticlockwise direction around the D's.

(i) State the direction of the magnetic field that is used in this cyclotron. *[1]*

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(ii) On the diagram, draw the path of a positive particle between the source and the detector. *[1]*

(iii) Explain why an alternating potential of a particular frequency is applied to the D's as shown. *[3]*

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(This question continues on the following page)

(Question J2 continued)

(b) Outline why much higher energies can be achieved in a synchrotron than in a cyclotron. *[3]*

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(c) In a particular experiment, protons in a synchrotron are accelerated to an energy of 2.0 GeV. Calculate the kinetic energy of the protons in GeV. *[1]*

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(d) In the Large Hadron Collider, protons can be accelerated to energies of 7 TeV. Deduce whether this value of energy is sufficient to mimic the temperature of the universe, 10^{32} K, shortly after the Big Bang. *[3]*

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J3. This question is about the standard model.

(a) State what is meant by the standard model. *[1]*

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(b) Use the conservation of lepton number and charge to deduce the nature of the particle *x* in the following reaction. *[1]*

$$v_e + \mu^- \rightarrow e^- + x$$

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(c) State what is meant by deep inelastic scattering. *[1]*

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(d) Outline how deep inelastic scattering experiments provide evidence for asymptotic freedom. *[2]*

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