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PHYSICS
HIGHER LEVEL
PAPER 3

Candidate session number

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Thursday 10 November 2011 (morning)

1 hour 15 minutes

Examination code

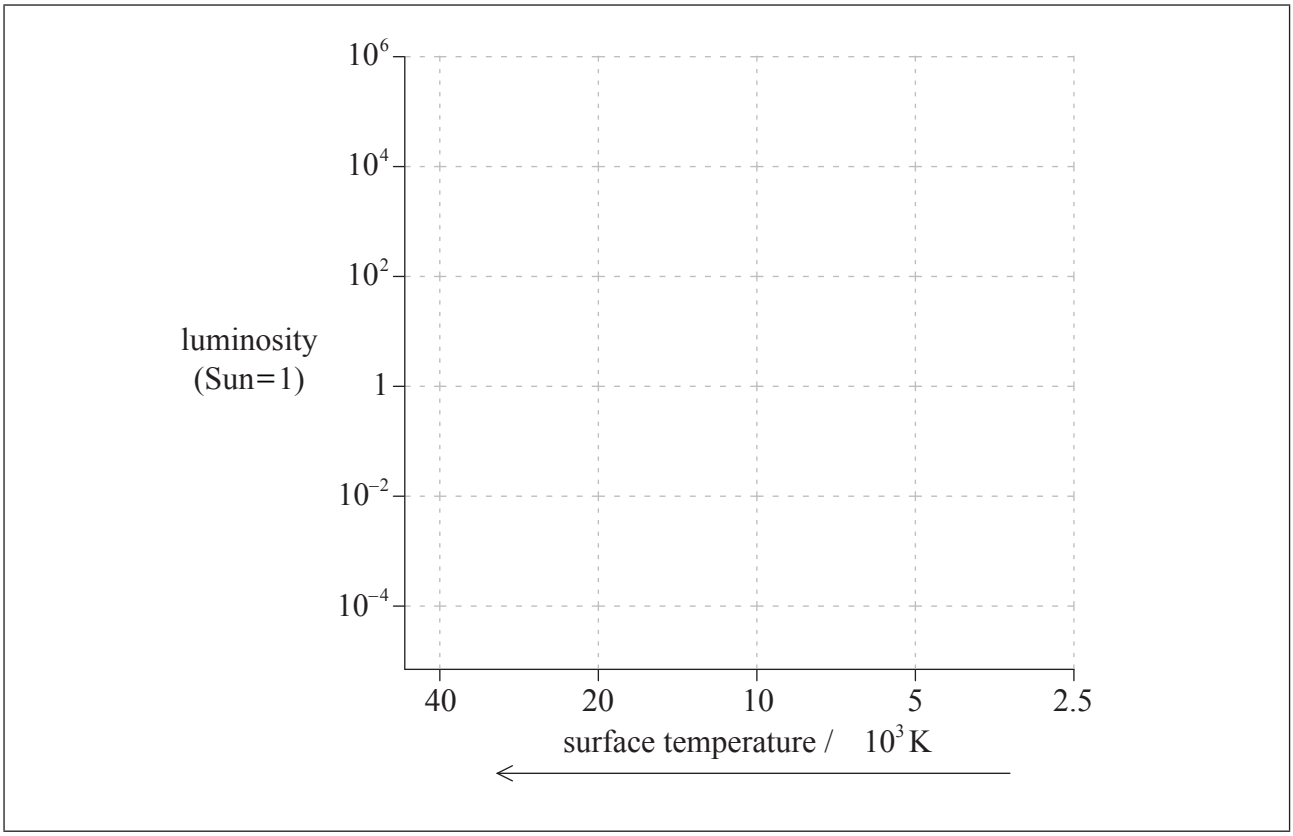
8	8	1	1	–	6	5	0	3

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.

Option E — Astrophysics

E1. This question is about stellar distances and stellar properties.



(a) On the grid of the Hertzsprung–Russell (HR) diagram shown, draw a line to represent the approximate position of the main sequence. *[2]*

(b) Barnard's star is a main sequence star that is 1.8 pc from Earth.

(i) Define the *parsec*. *[1]*

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(This question continues on the following page)

(Question E1 continued)

(ii) Calculate the parallax angle of Barnard's star as measured from Earth. *[1]*

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(c) Outline, using your answer to (b)(ii) and a labelled diagram, how the distance of Barnard's star from Earth is measured. *[3]*

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(Question E1 continued)

(d) The apparent brightness of Barnard's star is $3.6 \quad 10^{-12}\,\mathrm{W\,m^{-2}}$ and its surface temperature is 3800 K.

Given that $1\,\mathrm{pc} = 3.1 \quad 10^{16}\,\mathrm{m}$, show for Barnard's star

(i) that its luminosity is of the order of $10^{23}\,\mathrm{W}$. *[3]*

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(ii) that its surface area is of the order of $10^{16}\,\mathrm{m^2}$. *[3]*

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(e) On the HR diagram on page 2, draw the evolutionary path of Barnard's star after it leaves the main sequence. *[3]*

E2. This question is about the development of the universe.

(a) Light from distant galaxies, as seen by an observer on Earth, shows a red-shift. Outline why this observation suggests that the universe is expanding. *[2]*

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(b) The future development of the universe is determined by the relationship between the apparent density of the universe and the critical density.

(i) Define the term *critical density*. *[1]*

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(ii) Discuss how the density of the universe determines its future development. Your discussion should include **one** problem associated with determining the density of the universe. *[4]*

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E3. This question is about Hubble's law.

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

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(b) The wavelength of a line in the spectrum of atomic hydrogen, as measured in the laboratory, is 656 nm. The same line in the spectrum of light from a distant galaxy is measured to be 790 nm. The galaxy is 940 Mpc from Earth.

(i) Show that the recessional speed of the galaxy is $6.13 \ 10^4 \text{ km s}^{-1}$. *[2]*

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(ii) Determine, using your answer to (b)(i), a value for the Hubble constant. *[2]*

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(Question E3 continued)

(iii) Show, using your answer to (b)(ii), that the age of the universe is of the order of 10^{17} s. ($1\,\text{pc} = 3.1 \quad 10^{13}\,\text{km}$) *[2]*

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Option F — Communications

F1. This question is about modulation and bandwidth.

(a) Distinguish between a signal wave and a carrier wave. *[2]*

Signal wave: . . . . . .
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Carrier wave: . . . . . .
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(This question continues on the following page)

(Question F1 continued)

(b) Audio signals can be converted to electrical signals and then transmitted using a process called modulation.

Describe, with reference to your answer to (a), the process of

(i) amplitude modulation. *[2]*

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(ii) frequency modulation. *[3]*

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(Question F1 continued)

(c) A carrier wave of frequency f_c is amplitude modulated by a signal wave of a single frequency f_s. The bandwidth of the modulated wave is 10 kHz. There are $1.8\ 10^4$ complete oscillations of the carrier wave between two adjacent amplitude maxima of the carrier wave.

(i) Explain, with reference to the sideband frequencies of the modulated wave, why the frequency $f_s = 5.0$ kHz. *[3]*

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(ii) Show that the frequency $f_c = 90$ MHz. *[2]*

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F2. This question is about the digital transmission of information.

(a) State **two** advantages of using digital rather than analogue signals in the transmission of information. *[2]*

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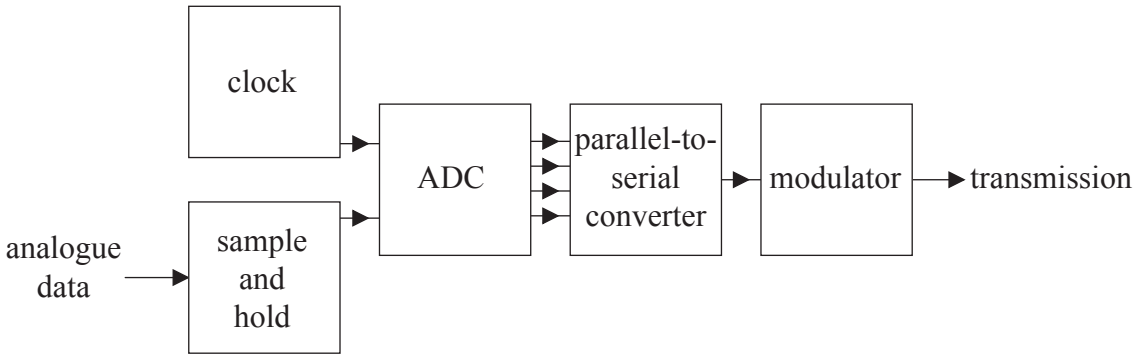
(b) The diagram shows the essential components of a digital data transmitter.



State the function of the

(i) clock. *[1]*

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(ii) ADC. *[1]*

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(This question continues on the following page)

(Question F2 continued)

(c) The transmitter in (b) is designed to transmit data at a rate of $2.0\,\text{Mb}\,\text{s}^{-1}$ using an 8-bit binary code. Calculate the frequency at which the sample and hold must operate. *[1]*

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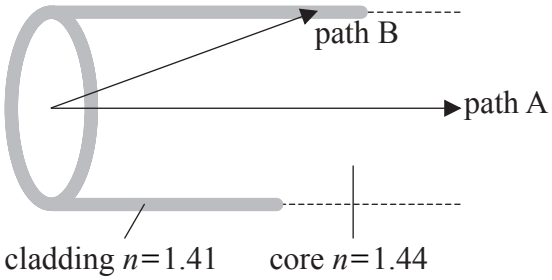
(Question F2 continued)

(d) Digital information that is transmitted along optic fibres is often subject to dispersion due to light taking different paths along the fibre.



In a particular optic fibre of length $2.00 \quad 10^4$ m, the refractive index of the cladding is 1.41 and that of the core is 1.44.

Two possible light paths are:

Path A: along the central axis of the fibre.

Path B: the path followed by light that is initially incident on the cladding at an angle just greater than the critical angle.

The speed of light in the core of the fibre is $2.10 \quad 10^8 \, \text{m s}^{-1}$.

Show that the difference in transmission time between path B and path A is approximately 2.0 μs. *[3]*

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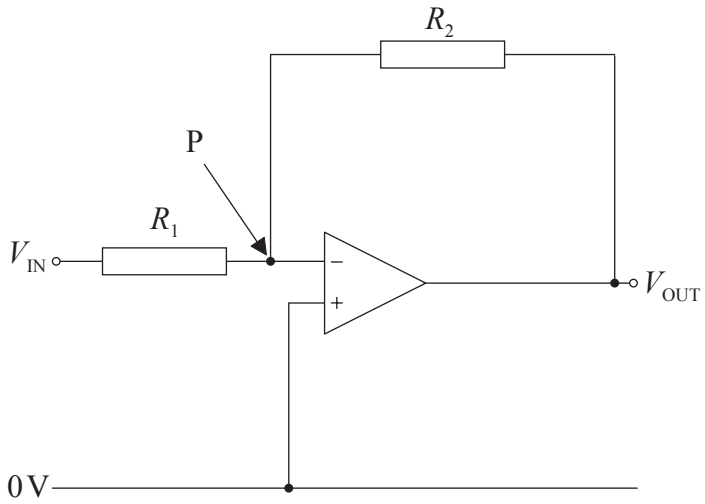
F3. This question is about operational amplifiers.

(a) The circuit diagram shows an operational amplifier connected as an inverting amplifier.



(i) Explain, with reference to the properties of an operational amplifier, why point P is effectively at zero potential. *[4]*

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(ii) Derive an expression for the gain G of the amplifier. *[2]*

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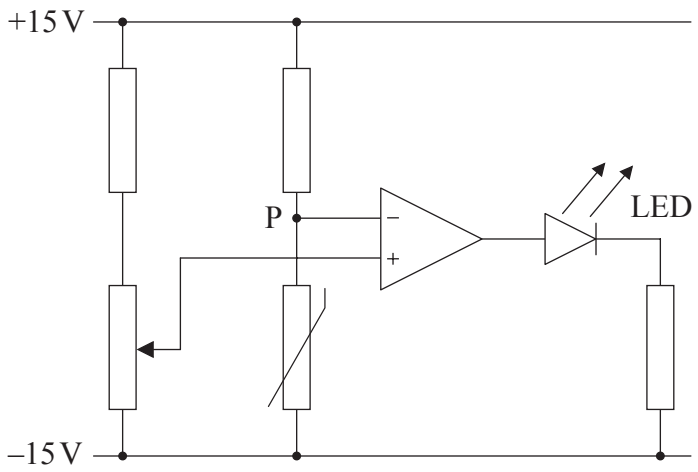
(Question F3 continued)

(b) In the circuit below, an operational amplifier is used as a comparator.



The amplifier operates from a ±15 V supply. If the thermistor reaches a certain temperature then, to act as a warning, the light-emitting diode (LED) switches on.

Describe, with reference to the potential at point P, the operation of the circuit. *[4]*

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Option G — Electromagnetic waves

G1. This question is about the electromagnetic spectrum.

(a) Outline the nature of electromagnetic waves. *[2]*

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(b) Explain why the ozone layer absorbs ultraviolet (UV) radiation. *[2]*

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G2. This question is about the compound microscope.

(a) A convex lens used as a magnifying glass has a focal length of f_e. Derive an expression for the angular magnification when the image is at the near point D. *[3]*

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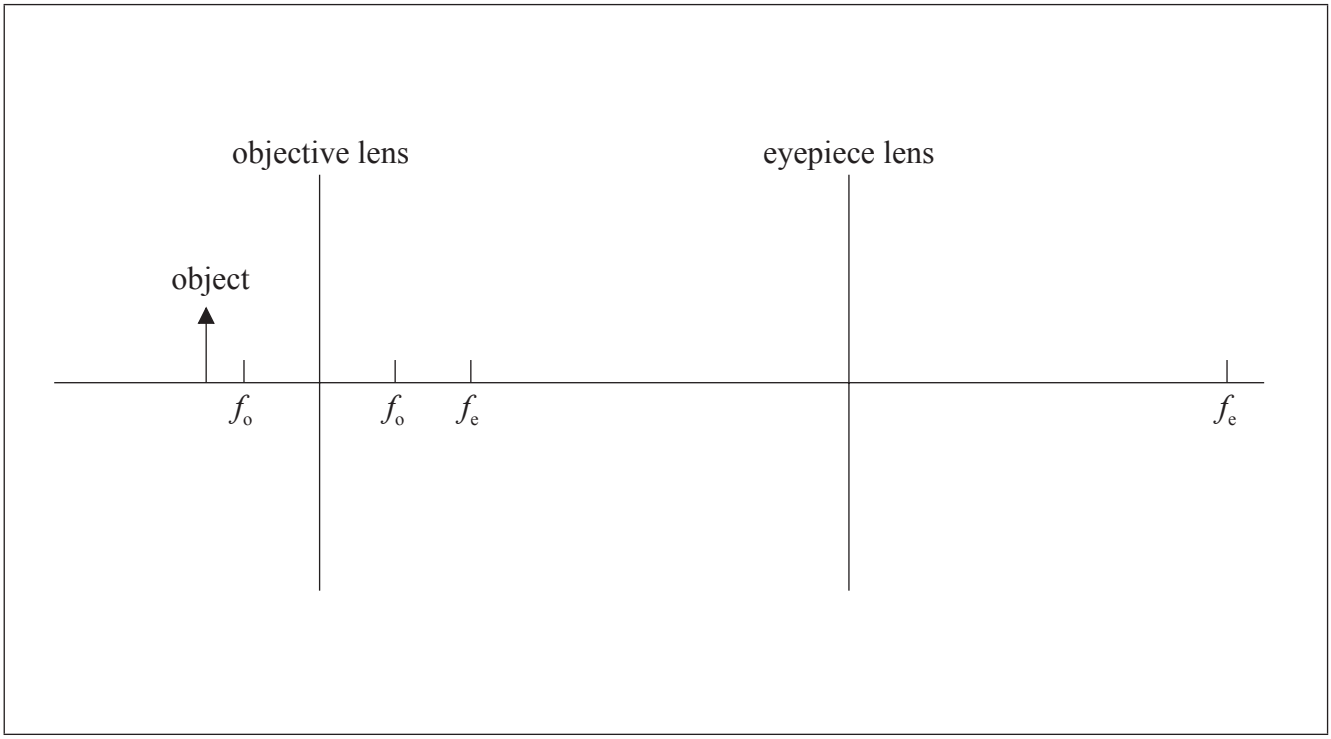
(Question G2 continued)

(b) The convex lens in (a) is used as the eyepiece of a compound microscope.



An object is placed 1.5 cm from the objective lens. The focal length f_o of the objective lens is 1.0 cm.

(i) Draw rays on the diagram to show the formation of the intermediate image. *[2]*

(ii) Calculate the distance of the intermediate image from the objective lens. *[2]*

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(This question continues on the following page)

(Question G2 continued)

(c) Lenses used in the compound microscope are subject to spherical aberration and chromatic aberration.

Explain what is meant by

(i) spherical aberration. *[2]*

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(ii) chromatic aberration. *[2]*

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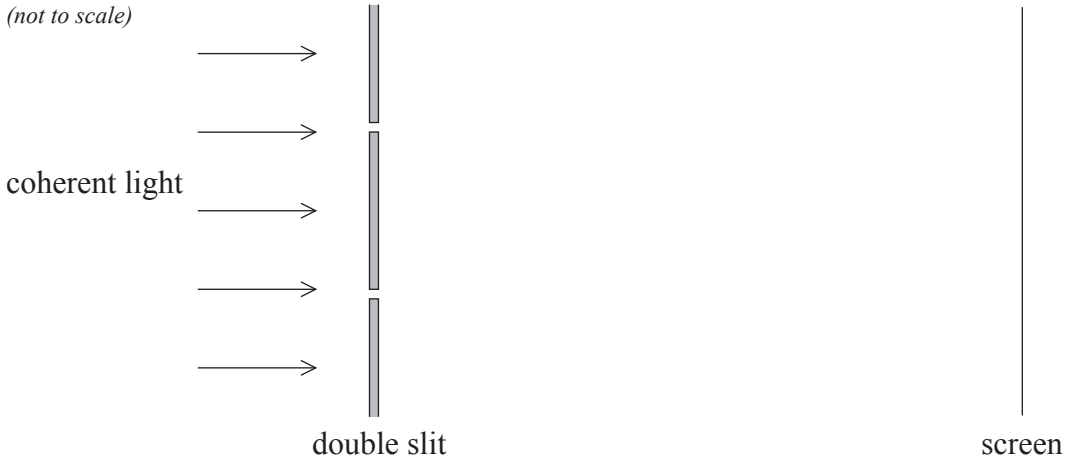
G3. This question is about two-source interference.

Coherent light is incident at right angles to a double slit. An interference pattern is observed on a distant screen.



(a) The width of both slits is now increased without altering their separation. State and explain the effect, if any, of this increase on the intensity of the bright fringes and the appearance of the dark fringes. *[3]*

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(b) The number of slits is now increased. State and explain the effect, if any, this has on the appearance of the bright fringes. *[2]*

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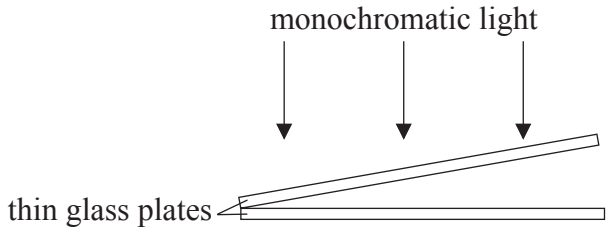
G4. This question is about wedge films.

The diagram shows two thin glass plates used to form a thin air wedge.



A beam of monochromatic light is incident on the air wedge. The reflected light is observed through a microscope and a pattern of equally spaced parallel fringes is observed.

(a) Outline how the fringes are formed. *[3]*

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(b) State and explain how the fringe separation changes if the angle of the wedge is increased slightly. *[2]*

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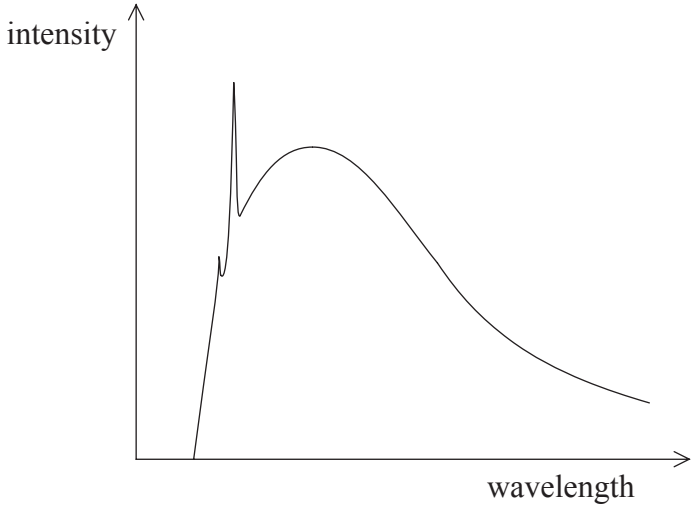
G5. This question is about X-rays.

The diagram shows the X-ray spectrum produced by the collision of electrons with a molybdenum target.



(a) Explain the formation of the characteristic spectra. *[3]*

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(b) The accelerating potential is 50 kV.

Calculate the minimum wavelength of X-rays produced. *[2]*

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Option H — Relativity

H1. This question is about special relativity, simultaneity and length contraction.

(a) One of the two postulates of special relativity may be stated as:

"The laws of physics are the same for all observers in inertial reference frames."

State

(i) what is meant by an inertial frame of reference. *[1]*

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(ii) the other postulate of special relativity. *[1]*

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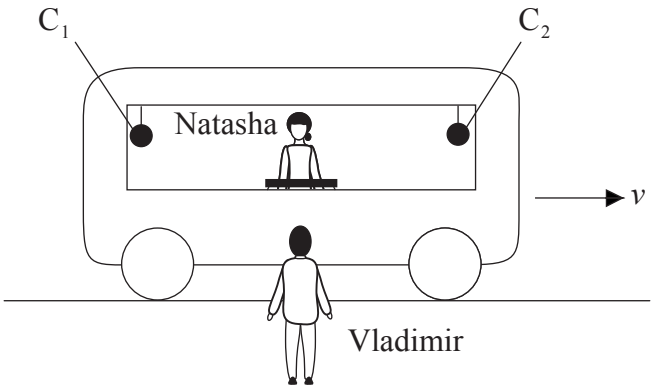
(This question continues on the following page)

(Question H1 continued)

(b) In a thought experiment to illustrate the concept of simultaneity, Vladimir is standing on the ground close to a straight, level railway track. Natasha is in a railway carriage that is travelling along the railway track with constant speed v in the direction shown.



Natasha is sitting on a chair that is equidistant from each end of the carriage. At either end of the carriage are two clocks C_1 and C_2. Next to Natasha is a switch that, when operated, sends a signal to each clock. The clocks register the time of arrival of the signals. At the instant that Natasha and Vladimir are opposite each other, Natasha operates the switch. According to Natasha, C_1 and C_2 register the same time of arrival of each signal.

Explain, according to Vladimir, whether or not C_1 and C_2 register the same time of arrival for each signal. *[4]*

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(This question continues on the following page)

(Question H1 continued)

(c) The speed v of the carriage is 0.70c. Vladimir measures the length of the table at which Natasha is sitting to be 1.0 m.

(i) Calculate the length of the table as measured by Natasha. *[3]*

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(ii) Explain which observer measures the proper length of the table. *[1]*

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(This question continues on the following page)

(Question H1 continued)

(d) According to Vladimir, a clock at rest in the railway carriage will appear to run slower than a clock at rest beside him. However, according to Natasha, Vladimir's clock will run slower than a clock at rest beside her.

(i) Outline how this time dilation phenomenon leads to the "twin paradox" in which one of the twins embarks on a return journey to a distant star at a speed close to that of light whilst the other twin remains on Earth. *[3]*

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(ii) State the reason behind the resolution of the paradox. *[1]*

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(This question continues on the following page)

(Question H1 continued)

(e) Evidence for time dilation comes from the decay of muons. A pulse of muons produced by cosmic radiation in the upper atmosphere of Earth travels to Earth with a speed of 0.96c as measured by an observer at rest on the surface of Earth. The half-life of the muons, as measured in the frame of reference in which the muons are at rest, is 3.1 10^{-6} s.

(i) Determine for the muons, the distance that Earth will have travelled towards them after half of the muons in the pulse have decayed. *[1]*

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(ii) Calculate for the Earth observer, the distance that the muon pulse will have travelled towards Earth after half of the muons in the pulse have decayed. *[2]*

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(f) Suggest how your answers to (e)(i) and (e)(ii) provide evidence that supports the theory of special relativity. *[3]*

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H2. This question is about relativistic energy and momentum.

(a) A proton is accelerated from rest through a potential difference V. The proton reaches a speed of 0.970c. Determine the value of V. *[3]*

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(b) Calculate, after acceleration for the proton in (a), its

(i) mass. *[1]*

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(ii) momentum. *[1]*

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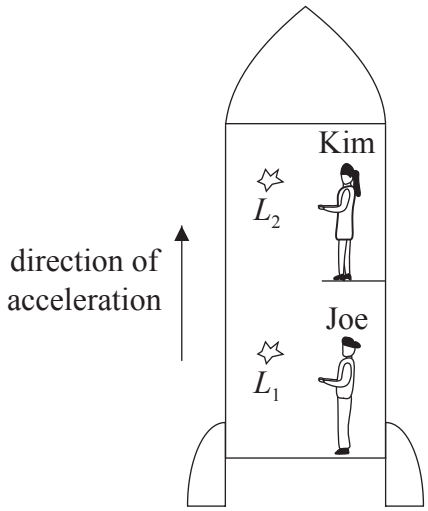
H3. This question is about the principle of equivalence and red-shift.

Joe and Kim are travelling in a spaceship.



Joe is next to a light source L_1 and Kim is next to an identical light source L_2.

The acceleration of the spaceship is zero. Kim measures the frequency of the light from L_1 to be the same as the frequency of the light from L_2.

(a) Outline why, if the spaceship now accelerates, Kim will measure the light from L_1 to be red-shifted with respect to the light from L_2. *[3]*

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(Question H3 continued)

(b) Suggest, with reference to Einstein's principle of equivalence, how your answer to (a) leads to the idea that a clock near a massive body runs more slowly than a clock in free space. *[2]*

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Option I — Medical physics

I1. This question is about sound intensity levels.

(a) Define, with reference to sound incident on the eardrum,

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

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

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(b) Explain why doubling the intensity of a sound incident on the eardrum of a person does not double the loudness of the sound as heard by the person. *[3]*

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(Question I1 continued)

(c) Two people standing 1.0 m apart are holding a conversation. The sound intensity of the conversation is approximately $10^{-6}\,W\,m^{-2}$. The intensity of a door slamming about 1.0 m away from one of the people is approximately $10^{-4}\,W\,m^{-2}$.

Estimate the difference in dB of the intensity levels of these two sounds. *[3]*

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I2. This question is about the use of ultrasound for diagnostic imaging.

(a) Outline how ultrasound is produced for use in diagnostic imaging. *[3]*

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(b) In order to look for damage to the chambers of the heart, ultrasound is used to form an image of the heart.

Suggest why it is better to use ultrasound rather than X-rays. *[2]*

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(c) The speed of sound in skin is about five times the speed of sound in air. Given that the density of skin is about 700 times that of the density of air, compare the acoustic impedance of skin to that of air. *[2]*

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(This question continues on the following page)

(Question I2 continued)

(d) Explain, using your answer to (c), why, in using ultrasound for imaging, a layer of gel is placed between the transducer and the skin. *[2]*

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(e) A wide range of frequencies of ultrasound may be used to image internal body organs. The choice of frequency for imaging a particular organ is determined by the depth of the organ beneath the skin.

Outline, with reference to attenuation and resolution, why the depth of the organ determines the choice of ultrasound frequency. *[4]*

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I3. This question is about dose equivalence of radioactive sources.

(a) Define *absorbed dose* as used in dosimetry. *[1]*

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(b) Both γ-radiation and α-radiation can be used in radiation therapy. However, γ-radiation has a quality factor of 1 whereas α-radiation has a quality factor of 20.

Outline the significance of this difference in quality factors in respect of radiation dosimetry. *[3]*

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(Question I3 continued)

(c) For safety purposes it is recommended that the dose equivalence of radioactive sources used in school laboratory experiments should not exceed 5.0 mSv. To measure the dose equivalent of a particular α source, the source was placed in an ionization chamber and the number of ion pairs produced by the source was measured.

Show, using the following data, if this source is safe to be used in school laboratory experiments. *[5]*

Number of ion pairs produced by source	$= 1.7 \quad 10^{10}$
Energy required to produce an ion pair	$= 34\,\text{eV}$
Quality factor of α-radiation	$= 20$
Volume of ionization chamber	$= 7.8 \quad 10^{-4}\,\text{m}^3$
Density of air	$= 1.2\,\text{kg}\,\text{m}^{-3}$

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Option J — Particle physics

J1. This question is about electrons and the weak interaction.

(a) State

(i) what is meant by an elementary particle. *[1]*

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(ii) to which class of elementary particles the electron belongs. *[1]*

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(b) An electron in an excited state of the hydrogen atom has an energy of 1.5 eV.

Show that the maximum time that the electron can spend in this state is $2.2 \quad 10^{-16}$ s. *[2]*

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(This question continues on the following page)

(Question J1 continued)

(c) An electron is one of the particles produced in the decay of a free neutron into a proton. An exchange particle is also involved in the decay.

(i) State the name of the exchange particle. *[1]*

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(ii) The weak interaction has a range of the order of 10^{-18} m. Determine, in GeV c^{-2}, the order of magnitude of the mass of the exchange particle. *[3]*

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(iii) It is suggested that the exchange particle in the weak interaction arises from the decay of one type of quark into another. With reference to the quark structure of nucleons, state the reason for this suggestion. *[2]*

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J2. This question is about particle accelerators.

(a) Charged particles in a cyclotron travel within two D-shaped, metal containers (Ds). There is a small gap between the Ds. An alternating potential is applied across this gap.

Outline why the frequency of the accelerating potential applied across the gap in the Ds is changed in order to increase the energy of the charged particles. *[4]*

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(b) A particular cyclotron is used to accelerate protons. The frequency of the alternating potential is 100 MHz. The radius of the Ds is 0.34 m. Show that the total energy of the accelerated protons is approximately 1200 MeV. *[4]*

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(This question continues on the following page)

(Question J2 continued)

(c) State the difference in structure of a synchrotron that enables the orbital radius of charged particles to be made much larger than in a cyclotron. *[1]*

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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) Muons can decay via the weak interaction into electrons and neutrinos. One such decay is

$$\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu}_\mu$$

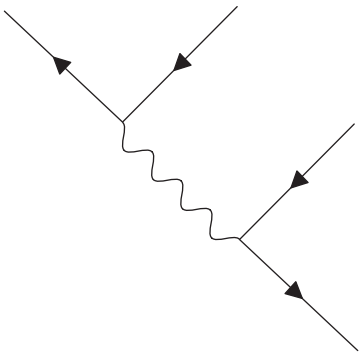
(i) Using the table provided, show that in this decay, lepton number L, electron lepton number L_e and muon lepton number L are all conserved. *[3]*

	μ^+	e^+	ν_e	$\overline{\nu}$
L				
L_e				
L_μ				

(This question continues on the following page)

(Question J3 continued)

(ii) Label the Feynman diagram below for the decay of a positive muon (μ^+). *[3]*



(c) Deep inelastic scattering provides evidence for the standard model.

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

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(ii) Discuss, with respect to the concept of momentum, how the results of deep inelastic scattering provide evidence for the existence of gluons. *[3]*

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