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International Baccalaureate®
Baccalauréat International
Bachillerato Internacional

PHYSICS
HIGHER LEVEL
PAPER 3

Tuesday 11 May 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.

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Option E — Astrophysics

E1. This question is about the relative population density of stars and galaxies.

The number of stars around the Sun, within a distance of 17 ly, is 75. The number of galaxies in the local group, within a distance of 4.0×10^6 ly from the Sun, is 26.

(a) Calculate the average population density, per ly^3, of stars and galaxies. *[2]*

Stars: . . . . . .

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Galaxies: . . . . . .

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(b) Use your answer to (a) to determine the ratio

$$\frac{\text{average population density of stars}}{\text{average population density of galaxies}}.$$ *[1]*

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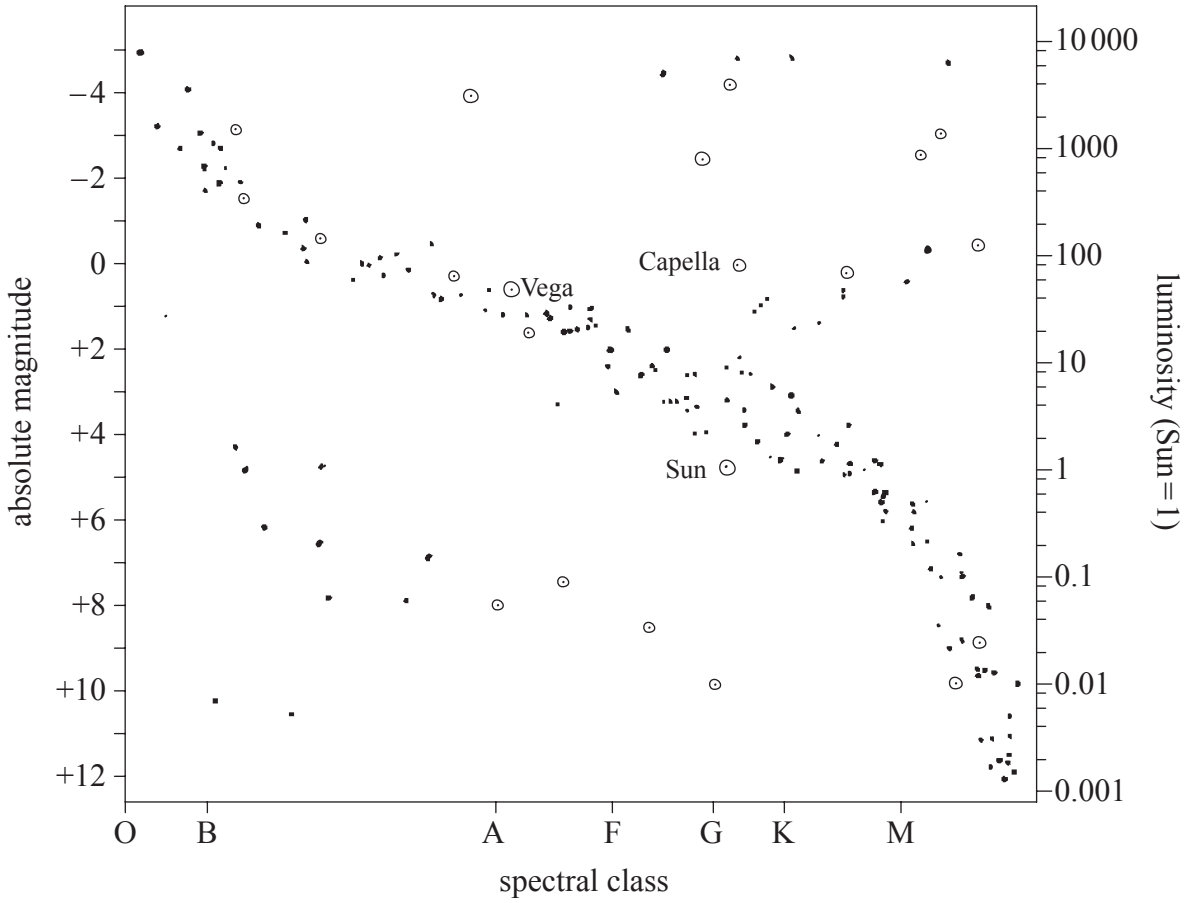
E2. This question is about the luminosity, size and distance of stars.

The Hertzsprung–Russell (HR) diagram shows the variation with spectral class of the absolute magnitude of stars.



The star Capella and the Sun are in the same spectral class (G). Using the HR diagram,

(a) (i) suggest why Capella has a greater surface area than the Sun. *[2]*

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(ii) estimate the luminosity of Capella in terms of that of the Sun. *[1]*

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(This question continues on the following page)

(Question E2 continued)

(iii) calculate the radius of Capella in terms of that of the Sun. *[2]*

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(b) The spectroscopic parallax method can be used to measure the distance of star Vega.

(i) Using the HR diagram, state the absolute magnitude of Vega. *[1]*

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(ii) The apparent magnitude of Vega is 0.0. Determine (in parsec) the distance of Vega from Earth. *[3]*

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(iii) Light from Vega is absorbed by a dust cloud between Vega and Earth. Suggest the effect, if any, this will have on determining the distance of Vega from Earth. *[2]*

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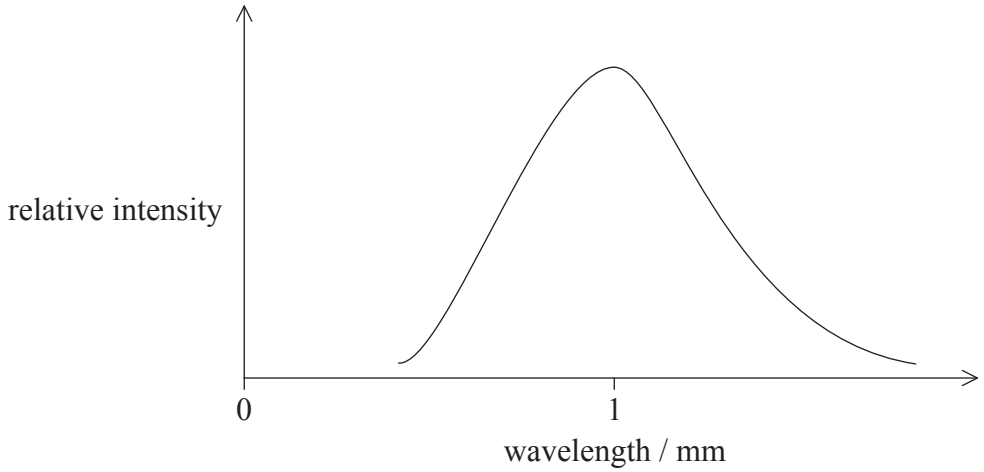
E3. This question is about cosmic microwave background radiation (CMB) and the density of the universe.

The graph shows the relative intensity of the CMB as a function of wavelength.



(a) Explain how this graph is consistent with the Big Bang model of the universe. *[3]*

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(b) The density of the universe will determine its ultimate fate. Outline the problems associated with determining the density of the universe. *[2]*

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(c) Outline how the expansion of the universe ultimately made it possible for stable nuclei and atoms to exist. *[1]*

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E4. This question is about the mass–luminosity relation and also the evolution of stars.

The mass–luminosity relation for main sequence stars is assumed to be $L \propto M^{3.5}$, where L is the luminosity and M is the mass. Star X is 8×10^4 times more luminous than the Sun and 25 times more massive than the Sun.

(a) Deduce that star X is a main sequence star. *[2]*

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(b) Outline with reference to the Oppenheimer–Volkoff limit, the evolutionary steps and the fate of star X after it leaves the main sequence. *[3]*

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E5. This question is about Hubble's law and the expansion of the universe.

(a) The spectrum of the cluster of galaxies Pegasus I shows a shift of 5.04 nm in the wavelength of the K-line. The wavelength of this line from a laboratory source is measured as 396.8 nm. Calculate the velocity of recession of the cluster. *[2]*

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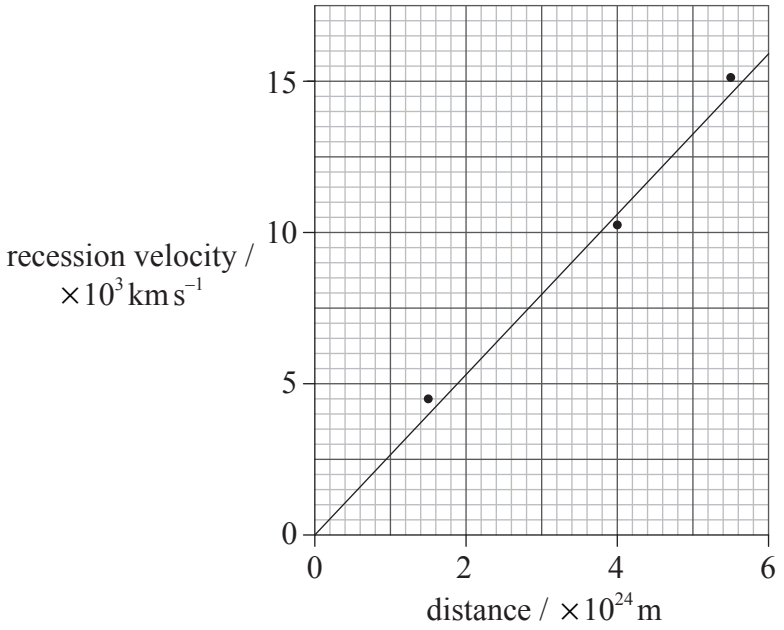
(b) The graph shows the recession velocities of a number of clusters of galaxies as a function of their approximate distances.



(i) State **one** method by which the distances shown on the graph could have been determined. *[1]*

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(ii) Use the graph to show that the age of the universe is about 10^{17} s. *[2]*

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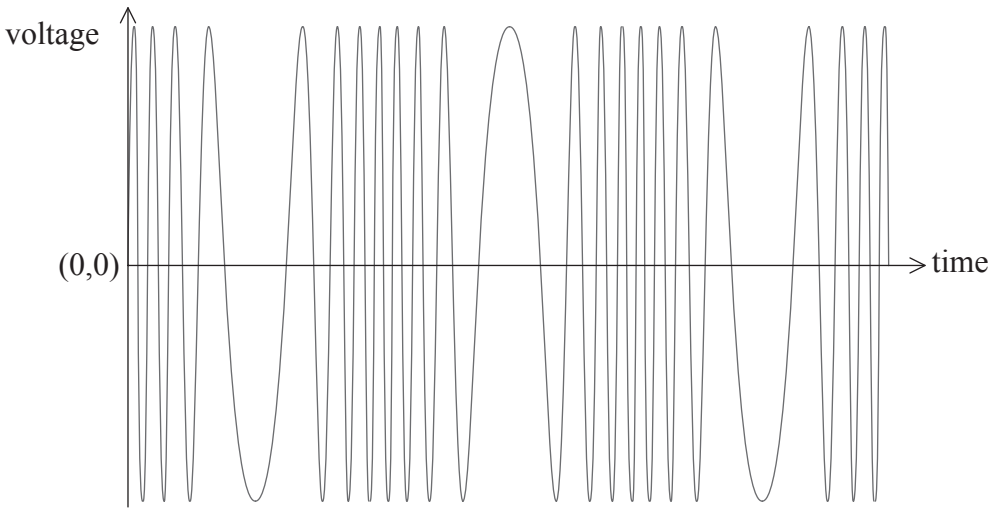
Option F — Communications

F1. This question is about modulation.

(a) The diagram shows how the voltage signal of a frequency modulated (FM) carrier wave varies with time.



The carrier wave is modulated by a single frequency signal.

On the above axes sketch the information signal. *[1]*

(b) State and explain **one** advantage of using FM modulation rather than amplitude modulation (AM). *[2]*

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F2. This question is about sampling.

A telephone call is sampled with a sampling frequency of 8.0 kHz. Each sample is stored as a four bit binary number. The duration of each bit in the sample is 4.0 μs.

(a) Calculate the time interval between the end of one sample and the beginning of the next. *[3]*

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(b) Outline, with reference to your answer in (a), what is meant by time-division multiplexing. *[2]*

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F3. This question is about the mobile phone system.

In the mobile phone system, a particular geographic area is divided into a number of cells with a base station in each cell, each connected to a cellular exchange.

Describe the function of the base stations and the cellular exchange. *[4]*

Base stations: . . . . . .
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Cellular exchange: . . . . . .
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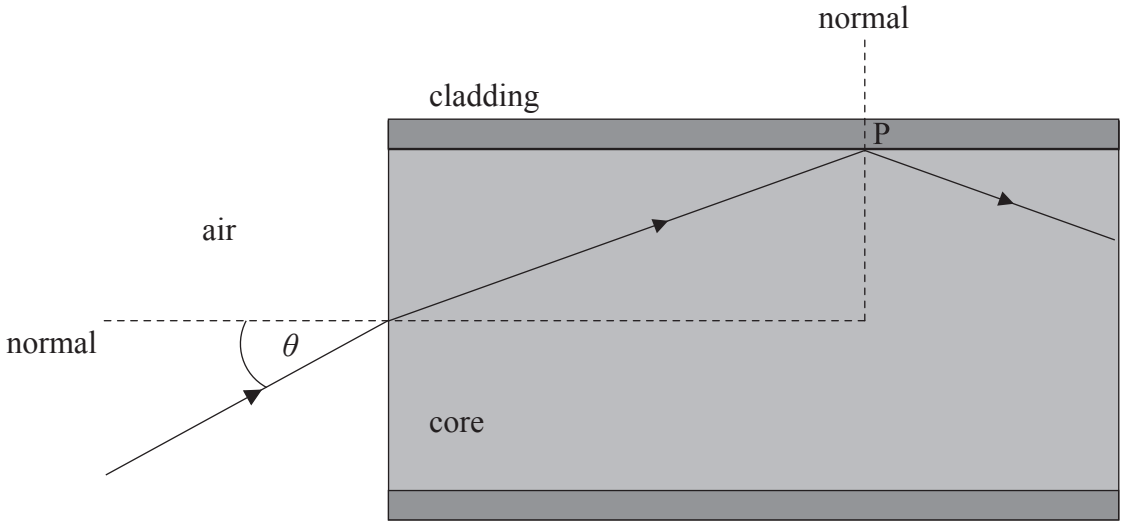
F4. This question is about the transmission of signals along an optic fibre.

(a) A ray of light enters an optic fibre from air. The ray makes an angle θ with the normal. The ray undergoes total internal reflection at point P.



The refractive index of the core is 1.56 and that of the cladding is 1.38.

(i) Calculate the critical angle of the cladding-core boundary. *[2]*

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(ii) Show that the largest angle of incidence θ in air, at which total internal reflection at the cladding-core boundary takes place, is 46.7°. *[2]*

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(Question F4 continued)

(b) Distinguish between modal dispersion and material dispersion in an optic fibre. *[2]*

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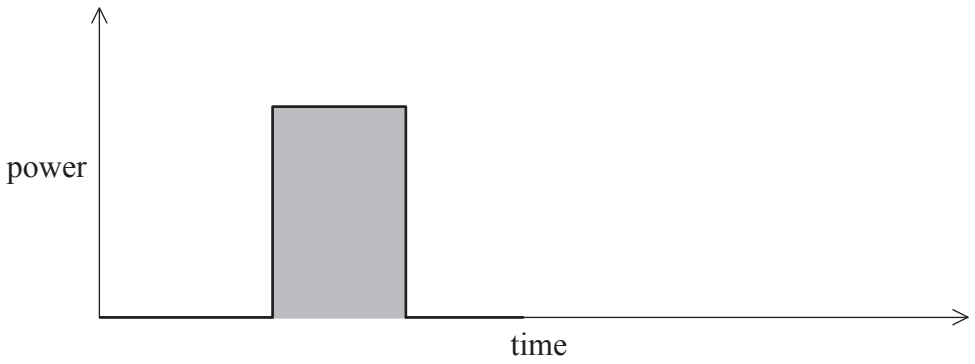
(c) The signal shown is fed into a monomode optic fibre.



(i) State what the shaded area represents. *[1]*

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(ii) Use the axes above to draw the shape of the signal after it has travelled a large distance in the fibre. *[2]*

(iii) The input signal power in a monomode fibre is 15.0 mW. The attenuation per unit length for this fibre is 1.24 dB km^{-1}. Determine the power of the output signal after the signal has travelled a distance of 3.40 km in the fibre. *[3]*

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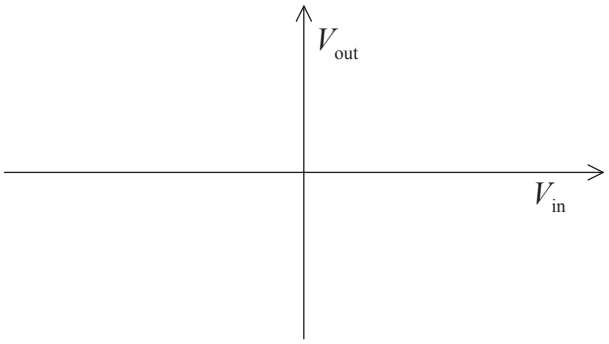
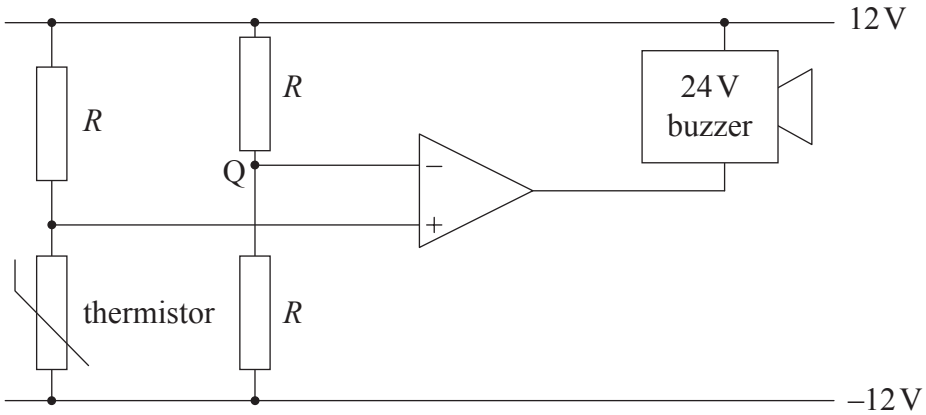
F5. This question is about the operational amplifier.

(a) On the axes below draw a sketch graph to show the variation with input voltage V_{in} of the output voltage V_{out} of a non-inverting operational amplifier. *[2]*



(b) A temperature warning device makes use of a buzzer that sounds when the potential difference across it is 24 V. The circuit in the warning device is shown.



It is required that the buzzer should sound when the temperature of the thermistor rises above 50 °C.

(i) State the voltage at point Q. *[1]*

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(ii) At a temperature of 50 °C the resistance of the thermistor is R. Explain why the buzzer will sound when the temperature rises above 50 °C. *[3]*

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Option G — Electromagnetic waves

G1. This question is about laser light.

(a) Outline how laser light is produced. *[3]*

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(b) State **two** ways in which light emitted by a laser differs from light emitted from an ordinary filament lamp. *[2]*

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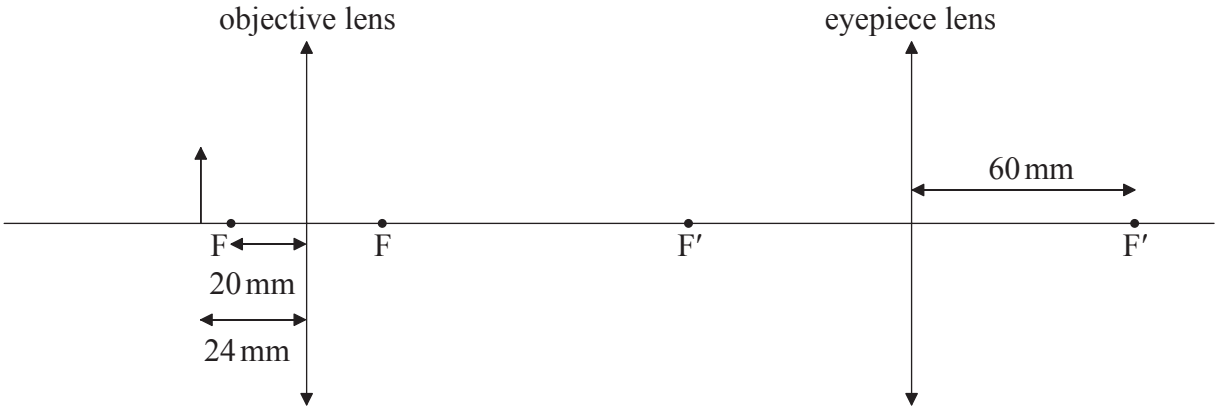
G2. This question is about a compound microscope.

The diagram (not to scale) is of a compound microscope.



The focal length of the objective lens is 20 mm and that of the eyepiece lens is 60 mm. A small object is placed at a distance of 24 mm from the objective lens. The microscope produces a final virtual image of the object at a distance of 240 mm from the eyepiece lens.

(a) (i) Determine, by calculation, the distance from the objective lens of the image formed by the objective lens. *[2]*

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(ii) Explain why the image in (a)(i) is real. *[1]*

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(iii) Determine the distance of the image formed by the objective lens from the eyepiece lens. *[2]*

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(b) Determine the overall magnification of the microscope. *[2]*

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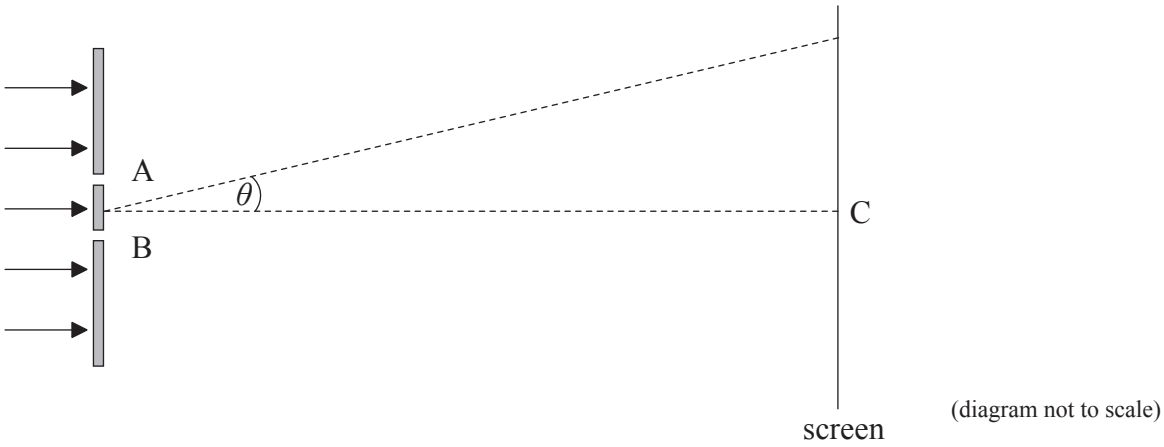
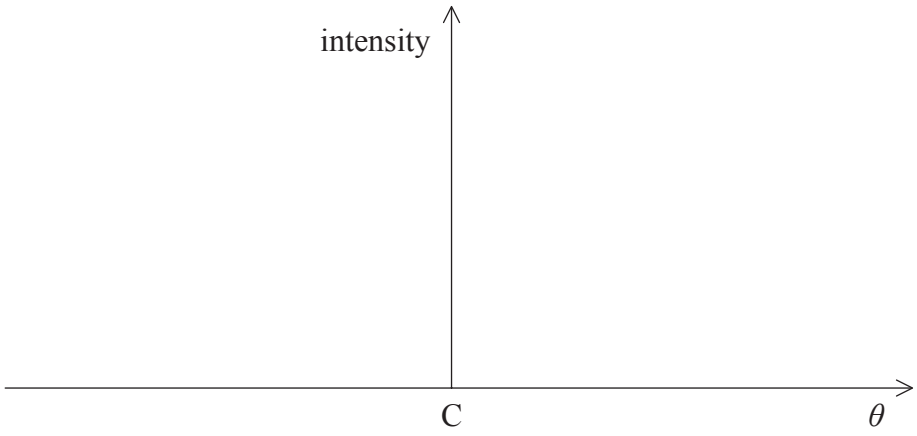
G3. This question is about interference.

(a) Light from a laser is incident on two very narrow slits A and B.



Point C on the screen is directly opposite the midpoint of the slits.

(i) On the axes below, sketch the variation with angle θ of the intensity of the light on the screen. *[2]*



(ii) The separation of the slits is 0.120 mm and the wavelength of the light is 6.80×10^{-7} m. The distance between the slits and the screen is 1.40 m. Calculate the separation of the bright fringes on the screen. *[2]*

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(This question continues on the following page)

(Question G3 continued)

(b) Slit A is covered with a transparent piece of glass. The effect of the glass is to increase the path length of the light from the slit to the screen by half a wavelength. It may be assumed that the amount of light absorbed by the glass is negligible. State and explain the effect(s), if any, of the glass on the

(i) intensity pattern you have drawn in (a)(i). *[2]*

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(ii) separation of the bright fringes calculated in (a)(ii). *[2]*

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G4. This question is about X-rays.

In an X-ray tube electrons are accelerated from rest through a potential difference and strike a metal target.

(a) On the axes below draw and annotate a typical X-ray spectrum. *[2]*

(b) Identify the mechanism by which the different regions of the X-ray spectrum are produced. *[3]*

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(c) In a particular X-ray tube the electrons are accelerated from rest through a potential difference of 24 kV. The minimum wavelength of the X-rays produced is 4.8×10^{-11} m. Determine a value for the Planck constant. *[3]*

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(d) X-rays of wavelength 2.25×10^{-10} m are directed towards the surface of a crystal. A strong first order reflected X-ray beam is observed when the X-rays make an angle of 28.1° with the crystal surface. Determine the separation of the atomic planes in the crystal. *[2]*

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Option H — Relativity

H1. This question is about frames of reference and the speed of light.

(a) Describe what is meant by an inertial frame of reference. *[2]*

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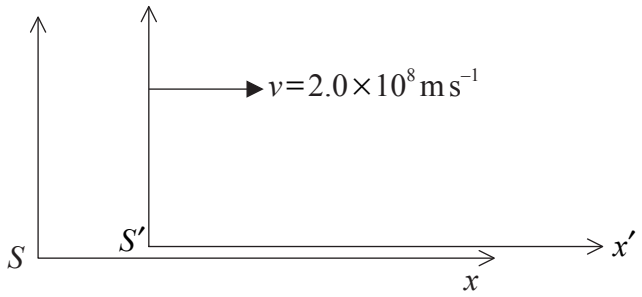
(b) The diagram shows two inertial frames of reference. Frame S' moves with velocity $v = 2.0 \times 10^8\ \text{m s}^{-1}$ relative to frame S along the x-x'-direction. When the origins of the two frames coincided, the clocks in both frames were set to show zero.



An event takes place at $x = 5.0 \times 10^3\ \text{m}$ when the clocks in frame S show $t = 3.0 \times 10^{-5}\ \text{s}$.

(i) By using Galilean transformation equations, determine the position and time of this event in the S' frame of reference. *[2]*

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(ii) A laser, at rest in the frame S', emits a ray of light along the negative x'-direction (*i.e.* towards the left). The speed of the ray of light is measured to be c in the frame S'. Show, using the relativistic velocity addition formula, that the speed of the ray of light in the frame S is also measured to be c. *[2]*

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(This question continues on the following page)

(Question H1 continued)

(c) Outline an experiment (other than the Michelson–Morley experiment) which provides evidence that the speed of light is independent of the speed of its source. *[2]*

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H2. This question is about relativistic kinematics.

(a) State what is meant by proper length and proper time interval. *[2]*

Proper length: . . . . . .

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Proper time interval: . . . . . .

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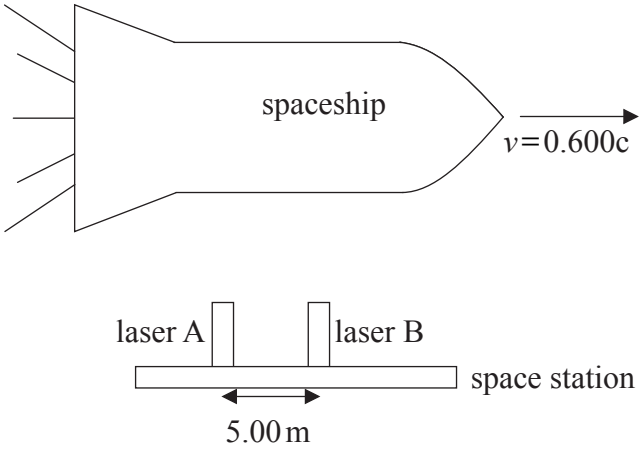
(b) A spaceship moves with speed $v = 0.600c$ relative to a space station. Two lasers, A and B, on the space station are 5.00 m apart as measured by the space station observers. The gamma factor for a speed of $v = 0.600c$ is $\gamma = 1.25$.



(i) A radio signal is sent to the spaceship from the space station. The transmission lasts for 6.00 s according to space station clocks. Calculate the duration of the transmission according to the spaceship observers. *[2]*

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(ii) Calculate the distance between the lasers A and B according to the spaceship observers. *[2]*

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(This question continues on the following page)

(Question H2 continued)

(c) The lasers in (b) are fired **simultaneously** according to the **space station** observers. Light from each laser makes a mark on the spaceship. The spaceship observers measure the distance between the two marks to be 6.25 m. According to the spaceship observers

(i) state which laser was fired first. *[1]*

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(ii) determine the difference in time between the firings of the two lasers. *[2]*

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H3. This question is about relativistic mechanics.

The upsilon $\left(\Upsilon^0\right)$ is an unstable particle that decays into a tau $\left(\tau^-\right)$ and an antitau $\left(\tau^+\right)$ according to the reaction

$$\Upsilon^0 \rightarrow \tau^- + \tau^+$$

The Υ^0 is at rest relative to the laboratory when it decays. The momentum of the τ^- relative to the laboratory is $4.40\,\text{GeV}\,\text{c}^{-1}$. The rest mass of the τ^- and of the τ^+ is $1.78\,\text{GeV}\,\text{c}^{-2}$.

Determine the rest mass of the Υ^0. *[3]*

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H4. This question is about general relativity.

(a) State Einstein's principle of equivalence. *[1]*

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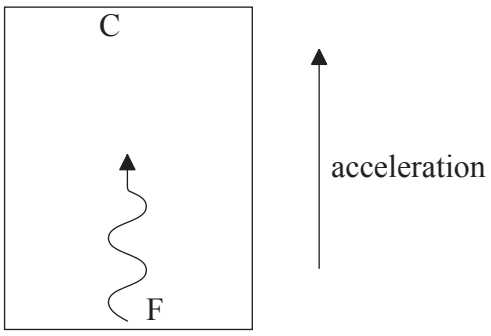
(b) A rocket is accelerating in the direction shown far from any masses.



A monochromatic beam of light is emitted from the floor F of the rocket. The beam is received at the ceiling C of the rocket. Suggest why the frequency of the light beam measured at C is less than the frequency measured at F. *[2]*

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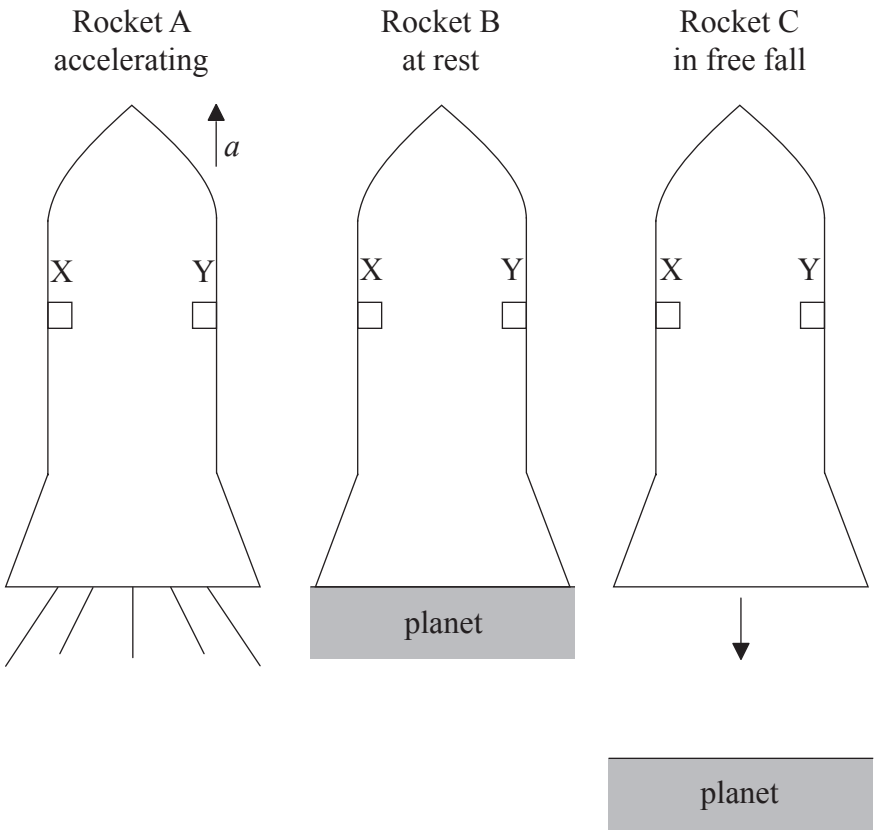
(Question H4 continued)

(c) The diagram shows three identical rockets A, B and C.



Rocket A is accelerating in outer space with acceleration a.

Rocket B is at rest on the surface of a planet. The gravitational field strength at the surface of the planet is a.

Rocket C is falling freely above a planet. The gravitational field strength of the planet in the region of the rocket is a.

Light is emitted from a source X on the left wall of each rocket. The receiver Y is directly opposite X.

The initial direction of the light is parallel to the floor of the rocket.

Draw, for each rocket, the path of the light ray emitted from X according to an observer in each rocket. *[3]*

(This question continues on the following page)

(Question H4 continued)

(d) Einstein's theory of general relativity predicts that a massive body causes a curvature (bending) of space.

(i) Describe what is meant by the curvature of space. *[1]*

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(ii) Describe how Eddington's experiment provides evidence for the curvature of space caused by the Sun. *[3]*

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Option I — Medical physics

I1. This question is about the ear and hearing.

(a) State the physical property of a sound wave that is related to the intensity of the sound. *[1]*

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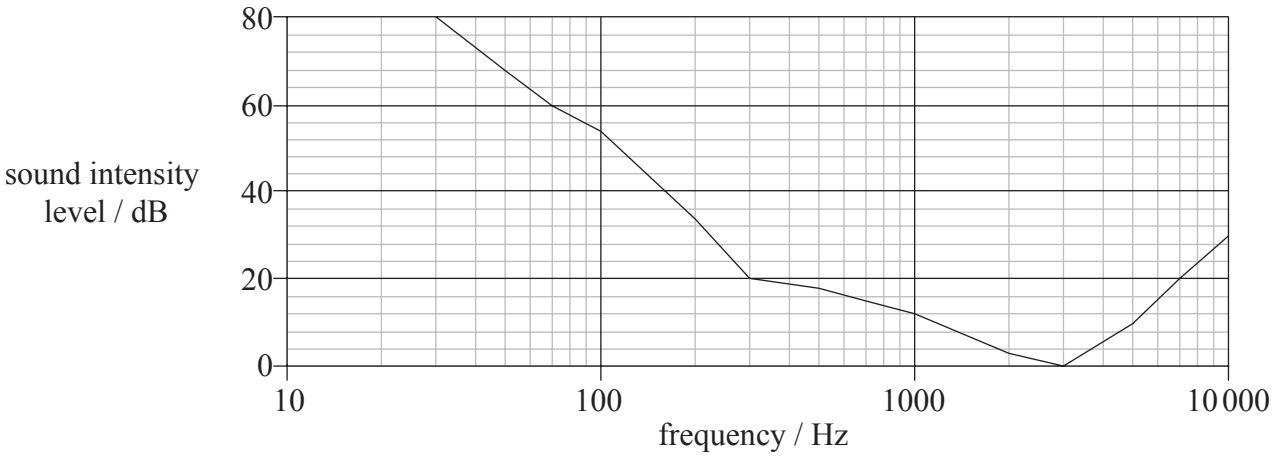
(b) The graph shows the variation with frequency of the threshold of hearing for a person with normal hearing.



Calculate the intensity of sound of frequency 600 Hz that can just be heard by this person. *[3]*

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(c) As a result of long-term exposure to noise a person suffers from a hearing loss of 20 dB.

(i) On the axes in (b) draw a sketch graph to show the variation with frequency of the threshold of hearing for this person. *[1]*

(ii) Explain why this loss is likely to lead to difficulties with speech recognition. *[2]*

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I2. This question is about ultrasound.

(a) Define *acoustic impedance*. *[1]*

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(b) Ultrasound of intensity I_0 is travelling in a medium of impedance Z_1 and is incident on a medium of impedance Z_2. The reflected ultrasound has intensity I_R given by the following equation.

$$\frac{I_R}{I_0} = \left(\frac{Z_1 - Z_2}{Z_1 + Z_2} \right)^2$$

Explain why when using ultrasound a gel is placed between the transducer and the skin of the patient. *[4]*

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I3. This question is about X-rays.

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

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(b) The half-value thickness in metres of air at pressure p and temperature T is given by the equation

$$x_{\frac{1}{2}} = 1.8 \times 10^5 \times \frac{T}{p}$$

X-rays from the Sun reach the outer layers of the atmosphere of Earth.

The following data are available.

Average pressure of the atmosphere	$= 2.0 \times 10^4$ Pa
Average temperature of the atmosphere	$= 240$ K
Effective height of the atmosphere	$= 25$ km

Using the data, calculate the

(i) half-value thickness for the atmosphere. *[2]*

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(ii) fraction of the incident X-ray intensity that is transmitted to the surface of the Earth. *[3]*

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(c) Comment, using your answer to (b)(ii), on whether the atmosphere provides any significant protection from incoming X-rays. *[1]*

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(This question continues on the following page)

(Question I3 continued)

(d) X-ray photons of average energy 20 keV are incident at a height of 10 km above the Earth's surface at a rate of $2.8 \times 10^8\,m^{-2}\,s^{-1}$. A passenger is in a plane flying at a height of 10 km above the surface of the Earth. The passenger has a mass of 60 kg and body surface area $1.6\,m^2$.

The quality factor for X-rays is 1.

(i) Calculate the dose equivalent received by this passenger during a three hour flight at a height of 10 km. *[4]*

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(ii) State **one** reason why the dose equivalent received will be much less than your answer in (d)(i). *[1]*

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I4. This question is about radio-isotopes.

(a) State what is meant by the effective half-life of a radio-isotope. *[2]*

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(b) The function of the lungs may be monitored using the radio-isotopes $^{133}_{54}\text{Xe}$ and $^{81}_{36}\text{Kr}$. Information on these two radio-isotopes is given in the table.

Radio-isotopes	Effective half-life	Decay products
$^{133}_{54}\text{Xe}$	5.2 days	β^- and γ
$^{81}_{36}\text{Kr}$	12 seconds	γ

State and explain **one** advantage and **one** disadvantage of using $^{133}_{54}\text{Xe}$ rather than $^{81}_{36}\text{Kr}$. *[4]*

Advantage: . . . . . .

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Disadvantage: . . . . . .

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Option J — Particle physics

J1. This question is about quarks.

The table below gives the electric charge of the three lightest quarks in terms of *e*, the charge of the proton.

Quark flavour	up u	down d	strange s
Electric charge / *e*	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$

(a) Using the data in the table, determine the

(i) quark content of a meson with charge +1 and strangeness 0 and that of a baryon with charge –1 and strangeness –3. *[2]*

Meson: . . . . . .

Baryon: . . . . . .

(ii) possible spin values of the meson in (a)(i). *[1]*

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

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(This question continues on the following page)

(Question J1 continued)

(c) Explain how the baryon with quark content uuu and spin $\frac{3}{2}$ does not violate the Pauli exclusion principle. *[1]*

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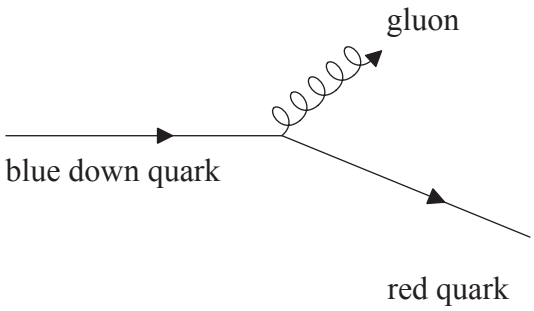
(d) In the Feynman diagram shown a blue down quark emits a gluon and produces a red quark.



Deduce the

(i) quark flavour (type) of the produced quark. *[1]*

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(ii) colour quantum numbers of the emitted gluon. *[1]*

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(This question continues on the following page)

(Question J1 continued)

(e) The positive kaon K^+ (quark content $u\bar{s}$) decays into an anti-muon and a neutrino according to the reaction below.

$$K^+ \rightarrow \mu^+ + v$$

Explain how it may be deduced that this decay is a weak interaction process. *[1]*

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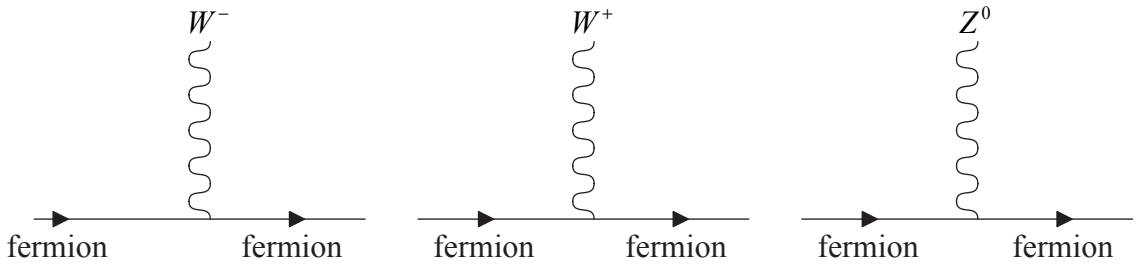
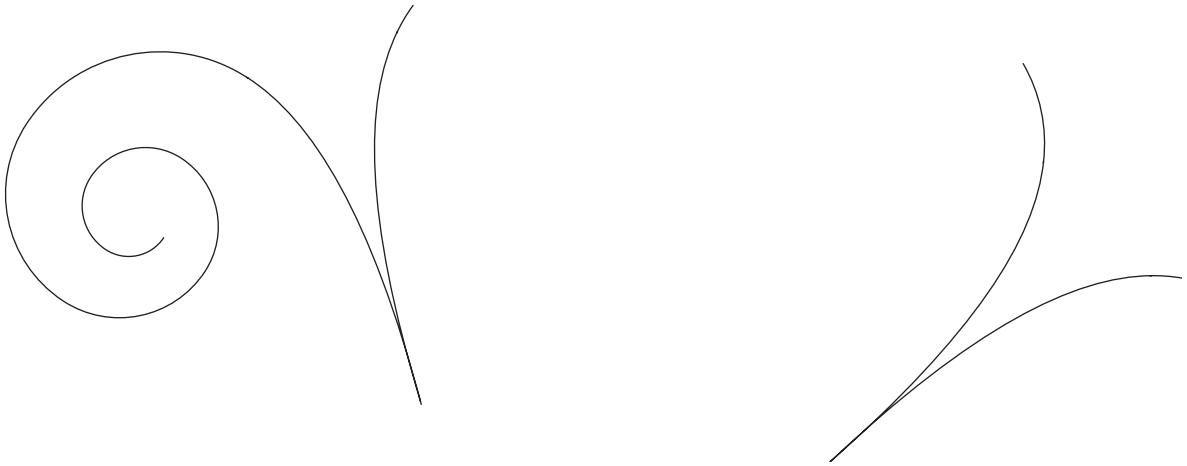
(f) The diagram shows three of the interaction vertices for the weak interaction.



Using the appropriate vertex, draw a Feynman diagram for the decay $K^+ \rightarrow \mu^+ + v$ labelling all particles involved. *[3]*

J2. This question is about the bubble chamber.

The diagram is a copy of a bubble chamber photograph of the decay of a neutral pion $\left(\pi^0\right)$ into two photons, $\pi^0 \rightarrow 2\gamma$. Each of the photons produced materializes into an electron–positron pair. The paths shown belong to the two electron–positron pairs.



(a) State why the tracks of the photons do not show up in the photograph. *[1]*

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(b) On the diagram above,

(i) draw lines to indicate the path of each of the photons. *[1]*

(ii) label with the letter P the point where the pion decayed. *[1]*

(This question continues on the following page)

(Question J2 continued)

(c) Outline whether the pion was moving **or** whether it was at rest when it decayed. *[2]*

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(d) The path of one of the electrons produced is a spiral. Suggest a reason for the shape of this path. *[1]*

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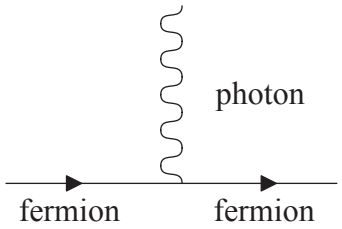
J3. This question is about Feynman diagrams and neutral currents.

(a) The diagram shows the interaction vertex of the electromagnetic interaction.



Hadrons may be produced via the electromagnetic interaction in electron–positron collisions through the reaction

$$e^- + e^+ \rightarrow q + \overline{q}$$

where q stands for a quark and $\overline{q}$ for an antiquark.

(i) Draw a Feynman diagram for the process $e^- + e^+ \rightarrow u + \overline{u}$ where u stands for the up quark. *[1]*

(ii) Outline why the reaction in (a)(i) eventually leads to the production of hadrons rather than individual quarks. *[2]*

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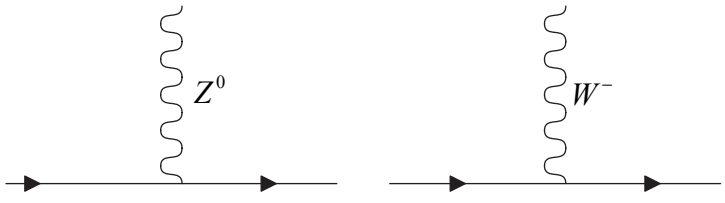
(This question continues on the following page)

(Question J3 continued)

(b) The diagram shows two vertices for the weak interaction.



The solid lines represent quarks or leptons.

(i) State what is meant by a neutral current. *[1]*

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(ii) Draw a Feynman diagram for the process $e^- + e^+ \rightarrow u + \overline{u}$, where u stands for an up quark, that is mediated by a neutral current. *[1]*

(This question continues on the following page)

(Question J3 continued)

(c) By reference to the weak interaction vertices in (b) suggest how the Z^0 may be detected. *[2]*

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(d) The W^- decays according to $W^- \rightarrow e^- + \overline{\nu}$. State and explain, whether the antineutrino in this decay is an electron, muon **or** tau antineutrino. *[3]*

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J4. This question is about the early universe.

For up to about 3×10^5 years after the Big Bang, photons were unable to penetrate the hydrogen gas in the universe. Suggest, without calculation, why this time had to elapse before photons could be transmitted through the hydrogen gas. *[3]*

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