RECOGNISING ACHIEVEMENT

OXFORD CAMBRIDGE AND RSA EXAMINATIONS
Advanced GCE

PHYSICS A — 2825/01

Cosmology

Monday **26 JANUARY 2004** Morning 1 hour 30 minutes

Candidates answer on the question paper.
Additional materials:
Electronic calculator

Candidate Name	Centre Number	Candidate Number

TIME 1 hour 30 minutes

INSTRUCTIONS TO CANDIDATES

- Write your name in the space above.
- Write your Centre number and Candidate number in the boxes above.
- Answer **all** the questions.
- Write your answers in the spaces provided on the question paper.
- Read each question carefully and make sure you know what you have to do before starting your answer.

INFORMATION FOR CANDIDATES

- The number of marks is given in brackets [ ] at the end of each question or part question.
- You may use an electronic calculator.
- You are advised to show all the steps in any calculations.
- The first five questions concern Cosmology. The last question concerns general physics.

FOR EXAMINER'S USE		
Qu.	**Max.**	**Mark**
1	10	
2	11	
3	13	
4	18	
5	18	
6	20	
TOTAL	90	

This question paper consists of 20 printed pages.

Data

speed of light in free space,	$c = 3.00 \times 10^{8}\ \mathrm{m\,s^{-1}}$
permeability of free space,	$\mu_0 = 4\pi \times 10^{-7}\ \mathrm{H\,m^{-1}}$
permittivity of free space,	$\epsilon_0 = 8.85 \times 10^{-12}\ \mathrm{F\,m^{-1}}$
elementary charge,	$e = 1.60 \times 10^{-19}\ \mathrm{C}$
the Planck constant,	$h = 6.63 \times 10^{-34}\ \mathrm{J\,s}$
unified atomic mass constant,	$u = 1.66 \times 10^{-27}\ \mathrm{kg}$
rest mass of electron,	$m_e = 9.11 \times 10^{-31}\ \mathrm{kg}$
rest mass of proton,	$m_p = 1.67 \times 10^{-27}\ \mathrm{kg}$
molar gas constant,	$R = 8.31\ \mathrm{J\,K^{-1}\,mol^{-1}}$
the Avogadro constant,	$N_A = 6.02 \times 10^{23}\ \mathrm{mol^{-1}}$
gravitational constant,	$G = 6.67 \times 10^{-11}\ \mathrm{N\,m^{2}\,kg^{-2}}$
acceleration of free fall,	$g = 9.81\ \mathrm{m\,s^{-2}}$

Formulae

uniformly accelerated motion, $s = ut + \frac{1}{2}at^2$

$v^2 = u^2 + 2as$

refractive index, $n = \frac{1}{\sin C}$

capacitors in series, $\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \ldots$

capacitors in parallel, $C = C_1 + C_2 + \ldots$

capacitor discharge, $x = x_0 e^{-t/CR}$

pressure of an ideal gas, $p = \frac{1}{3}\frac{Nm}{V}<c^2>$

radioactive decay, $x = x_0 \, e^{-\lambda t}$

$t_{\frac{1}{2}} = \frac{0.693}{\lambda}$

critical density of matter in the Universe, $\rho_0 = \frac{3H_0^2}{8\pi G}$

relativity factor, $= \sqrt{(1 - \frac{v^2}{c^2})}$

current, $I = nAve$

nuclear radius, $r = r_0 A^{1/3}$

sound intensity level, $= 10 \lg\left(\frac{I}{I_0}\right)$

For Examiner's Use

Answer **all** the questions.

1 **(a)** **(i)** State Kepler's three laws of planetary motion.

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....[3]

(ii) State **one** similarity and **one** difference between Kepler's model of the Solar System and that of Copernicus.

similarity ....

....

difference ....

....[2]

(b) Triton, a moon of Neptune, has an orbital period of 5.88 days and its mean distance from Neptune is 3.55×10^5 km. Proteus, another moon of Neptune, is observed to orbit Neptune with a period of 1.12 days.
Calculate the mean distance of Proteus from Neptune.

distance = ... km [3]

(c) Explain why the orbital periods of the moons of Neptune may show small variations.

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....[2]

[Total: 10]

2 (a) (i) Explain the terms *apparent magnitude* and *absolute magnitude* for a star.

apparent magnitude ....

....

absolute magnitude ....

....[4]

(ii) Explain how apparent magnitude and absolute magnitude are related.

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....[2]

(b) Fig. 2.1 shows absolute magnitude and temperature data for five stars, labelled **A** to **E**.

star	absolute magnitude	temperature / K
A	0	5 000
B	+10	5 000
C	+5	6 000
D	+14	11 000
E	0	11 000

Fig. 2.1

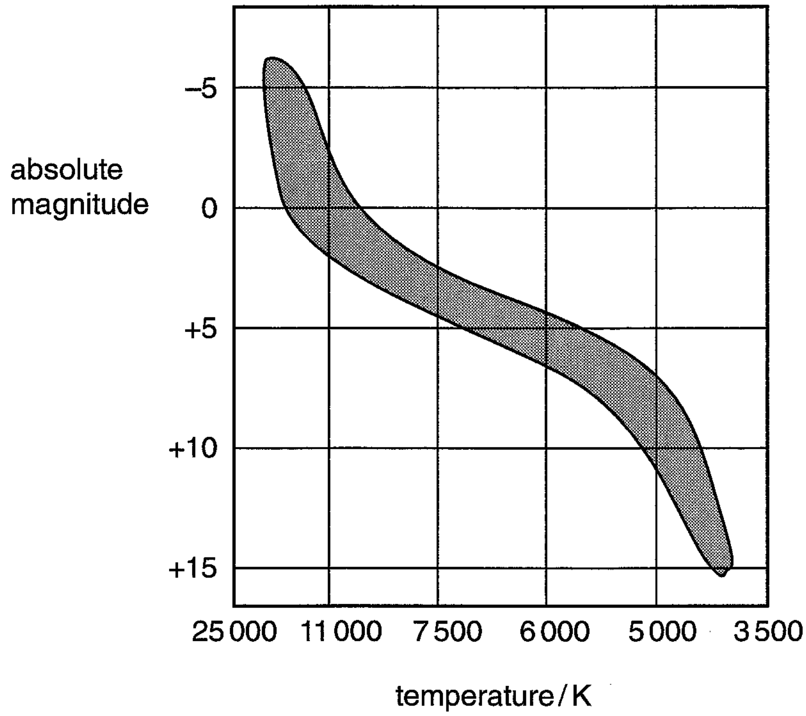

Fig. 2.2

Fig. 2.2 is a Hertzsprung-Russell diagram with the Main Sequence shaded.

(i) Plot and label the positions of stars **A** – **E** on Fig. 2.2.

(ii) Identify which of these stars is

1. the Sun ....
2. a red giant ....
3. a white dwarf ....
4. a star hotter and more massive than the Sun. .... [5]

[Total: 11]

For Examiner's Use

3 **(a)** Explain how Olbers' paradox and the work of Hubble on the motions of galaxies provide evidence for a finite Universe.

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....[6]

(b) The Hubble constant H_0 is given by the equation

$$H_0 = \frac{v}{r}$$

where v is the speed of recession of a galaxy and r is the distance from the observer to the galaxy.

(i) Some observations indicate a value for the Hubble constant of $H_0 = 70\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$. Convert this value into s^{-1}.

H_0 = ... s^{-1} [3]

For Examiner's Use

(ii) Hence estimate the age of the Universe.

age = ... s [1]

(iii) Use your answer to **(ii)** to estimate the maximum observable size for the Universe.

size = ... m [2]

(c) State an assumption you have made in answering **(b)**.

....

....[1]

[Total: 13]

4 **(a)** State the two postulates of special relativity and explain briefly why these postulates are incompatible with the Newtonian idea of absolute space. Explain why there is a maximum speed to which a body may be accelerated.

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....[6]

For Examiner's Use

(b) In an experiment to show time dilation in muons, identical detectors are set up at the top of a mountain and 2000 m below this point. Muons are generated naturally by cosmic ray bombardment and travel vertically downwards at high speed. The detector at the mountain top records 574 muons in one hour. The half-life $t_{\frac{1}{2}}$ of low speed muons measured in the laboratory is known to be 2.20 μs.

(i) Show that the time taken for muons to travel 2000 m at $3 \times 10^8\,\text{ms}^{-1}$ is equivalent to approximately three half-lives.

[2]

(ii) Hence estimate how many of the 574 muons originally detected at the top of the mountain would be expected to survive for the length of time calculated in **(i)**.

number of muons = ... [2]

(iii) The detector at the bottom of the mountain actually records 439 muons per hour. Explain this value in terms of time dilation.

....

....

....[3]

(iv) Calculate the observed fraction of muons which survive the 2000 m journey.

[1]

(v) The time dilation factor γ for the high-speed muons, is given by

$$\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}.$$

The speed of the muons is measured to be 0.992c. Show that this gives a time dilation factor of approximately 8.

[2]

(vi) Special relativity predicts the theoretical fraction f of muons surviving a journey of distance d is given by

$$\ln f = -\frac{d \ln 2}{\gamma v t_{\frac{1}{2}}}.$$

Use your answer to **(v)** to calculate f for $v = 0.992c$ and show that this is consistent with your answer to **(iv)**.

[2]

[Total: 18]

For Examiner's Use

5 One of the predictions of Einstein's theory of general relativity is that light will suffer deflection in the presence of a gravitational field.

(a) One form of the principle of equivalence states that uniform gravitational fields are indistinguishable from frames which accelerate uniformly relative to *inertial frames.* Explain what is meant by the term *inertial frame* and describe a thought experiment to explain how the equivalence principle predicts the bending of light in gravitational fields.

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....[6]

For Examiner's Use

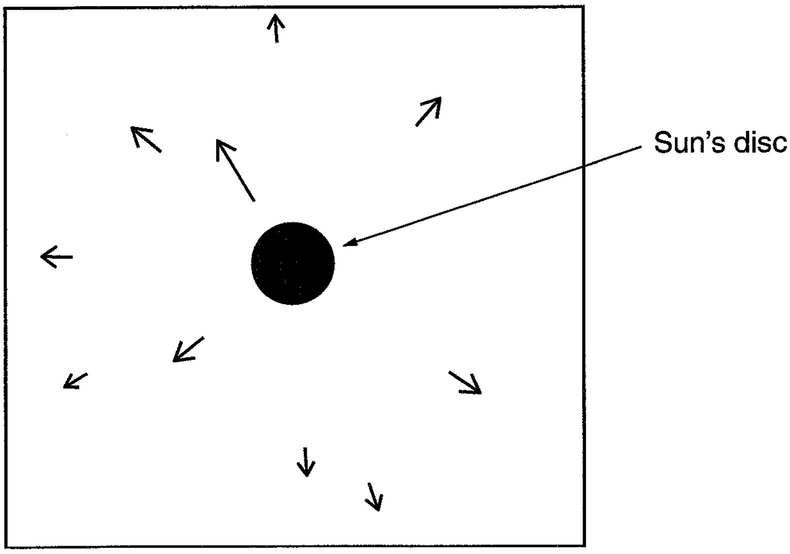

Fig. 5.1

(b) In 1919, Eddington measured the change in apparent position of stars during a solar eclipse to confirm Einstein's predictions. Observations at a further eclipse in 1922 yielded the results shown above in Fig. 5.1. The length of each arrow indicates the apparent displacement of a star during the eclipse (to a greatly enlarged scale).

(i) Explain why a total eclipse of the Sun was needed to test this effect.

....

....

....[2]

For Examiner's Use

(ii) With the aid of a diagram, explain why the stars closest to the disc of the Sun undergo the greatest apparent displacement.

....

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....

....[3]

(c) General relativity predicts that the angle of deflection α (in arc-seconds) should obey the equation

$$\alpha = \frac{k}{r}$$ **equation 5.1**

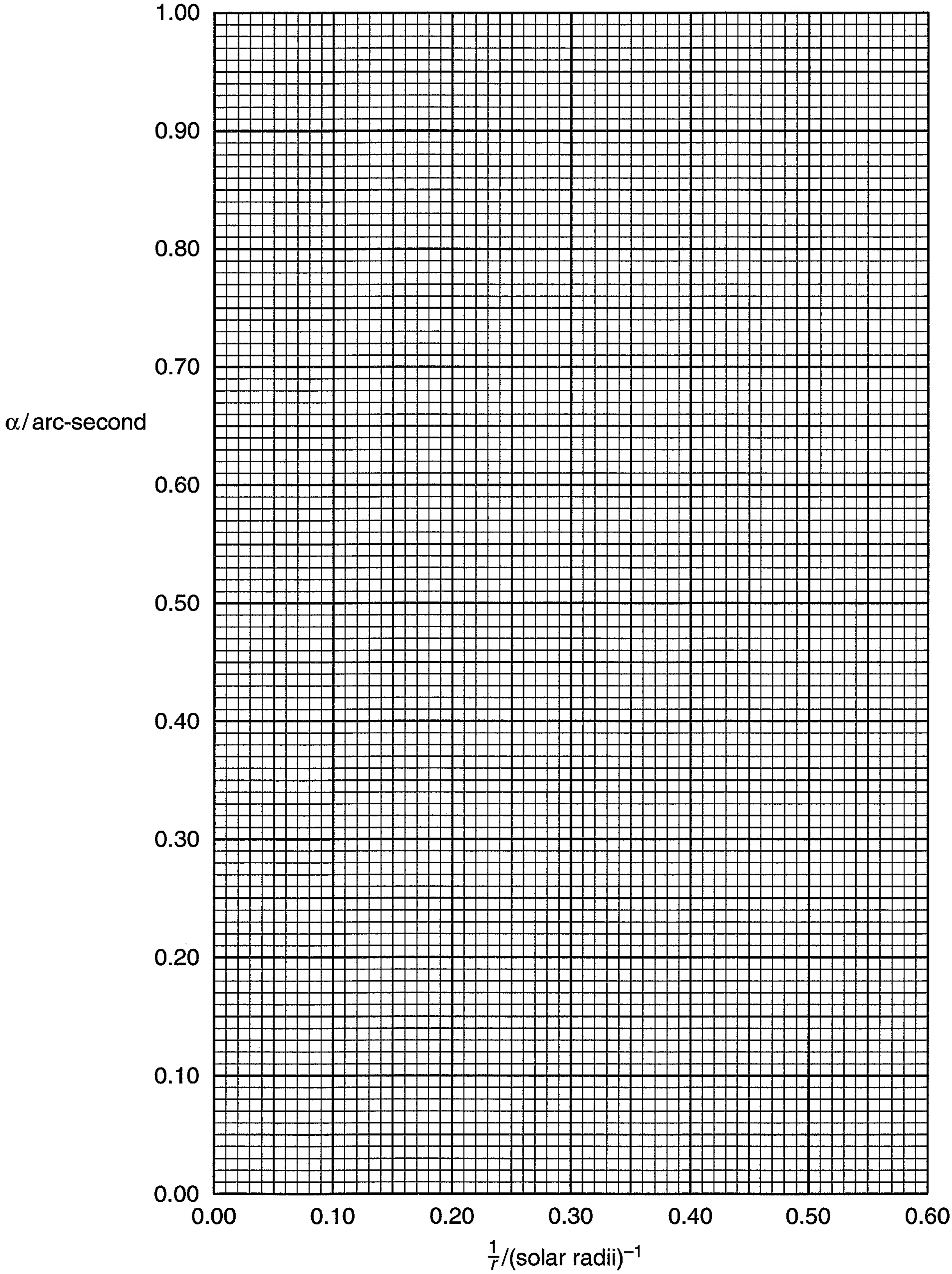
where r is the distance between the light path and the centre of the Sun and k is a constant. Measurements of the deflections of star images at different distances from the solar disc are shown in Fig. 5.2.

r/solar radius	α/arc-seconds	$\frac{1}{r}$/(solar radii)$^{-1}$
2.00	0.88	0.50
2.40	0.68	0.42
3.20	0.50	
4.30	0.43	
5.20	0.31	

Fig.5.2

(i) Complete the table. [1]

(ii) Plot a graph of α against $\frac{1}{r}$ on the grid provided. [2]


1.00
0.90
0.80
0.70
α / arc-second
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0.00
0.10
0.20
0.30
0.40
0.50
0.60
1/r /(solar radii)⁻¹

For Examiner's Use

(iii) Hence show that the data are consistent with equation 5.1.

....

....

....

....[2]

(iv) Use your graph to find a value for the constant *k*.

k = ... solar radii [1]

(v) *k* is related to the mass of the Sun, M_o, in kg by $k = 8.79 \times 10^{-31} M_o$. Hence find the mass of the Sun.

M_o = ... kg [1]

[Total: 18]

6 Scintillation counters have been widely used to detect particles in high energy physics experiments. A scintillation counter consists of a sheet of plastic scintillator material coupled to a photomultiplier tube, as shown in Fig. 6.1.

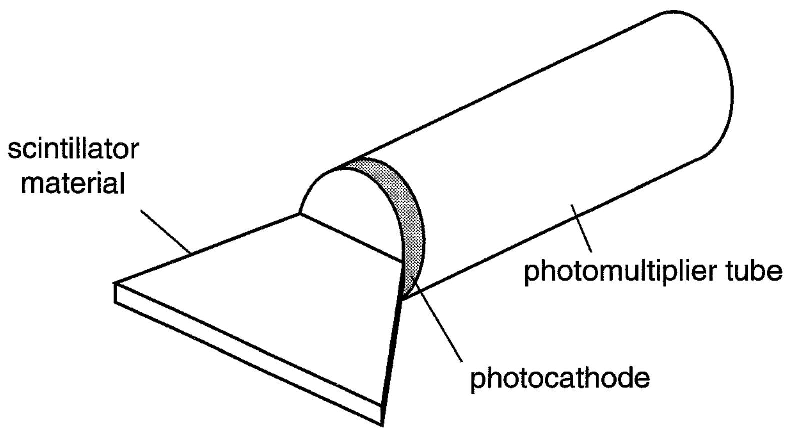


Fig. 6.1

The scintillator material produces a tiny flash of light when struck by a high energy particle. This light undergoes total internal reflection within the scintillator material until it reaches the photocathode of the photomultiplier tube. Fig. 6.2 shows this and also the internal structure of the photomultiplier tube.

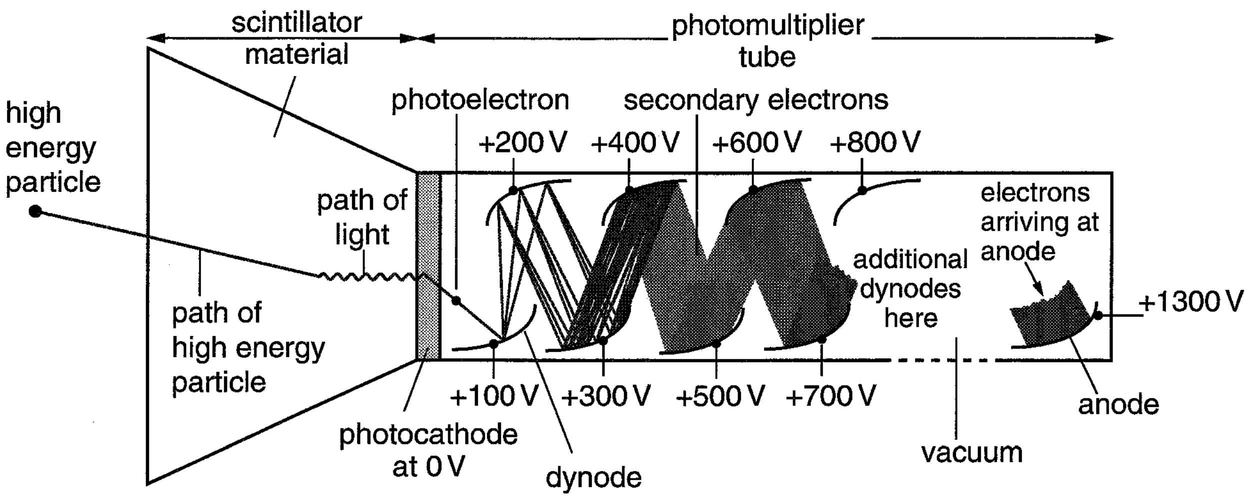


Fig. 6.2

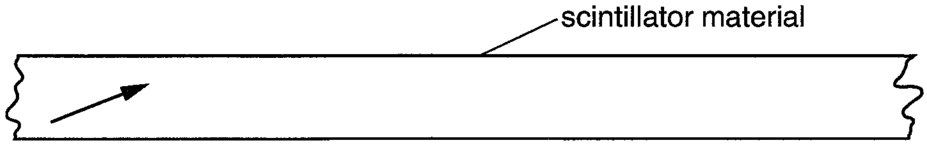
When the flash of light reaches the photocathode, the photoelectric effect causes an electron, called a photoelectron, to be emitted from the photocathode. This electron is attracted by a potential difference between the photocathode and the first curved plate, called a dynode. When the electron hits the first dynode, with 100 eV energy in this case, several *secondary* electrons are emitted. These are accelerated to the next dynode, where the process is repeated. The pulse of charge at the final dynode, called the anode, can be measured by an electronic system.

[Turn over

For Examiner's Use

(a) The diagram below shows a section of the scintillator viewed from the side.

(i) Explain, with the aid of the diagram, how the light may be transmitted along the scintillator by total internal reflection.



....

....

....

....[3]

(ii) The scintillator material has a refractive index of 1.58. Calculate the critical angle *C* for this material in air.

critical angle = ...° [2]

(b) In a particular experiment, a single high energy particle loses 1.5 MeV of energy in the scintillator material and in losing this energy produces 1.0×10^4 photons of wavelength 413 nm.

(i) Show that the energy of one photon of wavelength 413 nm is about 3.0 eV.

[2]

(ii) What percentage of the particle's energy loss has been converted into light in the scintillator material?

percentage = ...% [2]

For Examiner's Use

(c) The photocathode is coated with potassium which has a work function ϕ of 2.2 eV.

(i) Calculate the threshold wavelength for potassium.

threshold wavelength = ... nm [2]

(ii) Why would zinc, which has a work function of 4.3 eV, be unsuitable for the photocathode coating?

....

....[1]

(iii) Calculate the maximum speed v_{max} of the photoelectrons emitted from the potassium photocathode.

v_{max} = ... $m\,s^{-1}$ [3]

Question 6 continued over the page.

For Examiner's Use

(d) (i) In the photomultiplier tube, there are 13 dynodes, including the anode, and 3 secondary electrons are emitted at each dynode per incident electron. Calculate the number of electrons received at the anode for one electron leaving the photocathode.

number = ... [2]

(ii) This pulse of electrons lasts 3.0×10^{-9} s. Calculate the average current during this pulse.

average current = ... A [3]

[Total: 20]

END OF QUESTION PAPER