OXFORD CAMBRIDGE AND RSA EXAMINATIONS

Advanced GCE

PHYSICS A

2825/04

Nuclear and Particle Physics

Thursday **22 JUNE 2006** Afternoon 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 that 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.
- Your may use an electronic calculator.
- You are advised to show all the steps in any calculations.
- The first six questions concern Nuclear and Particle Physics. The last question concerns general physics.

FOR EXAMINER'S USE

Qu.	Max.	Mark
1	12	
2	12	
3	9	
4	15	
5	15	
6	7	
7	20	
TOTAL	90	

This question paper consists of 19 printed pages and 1 blank page.

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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, $n = \dfrac{1}{\sin C}$

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

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

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

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

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

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

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

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

current, $I = nAve$

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

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

Answer **all** the questions.

1 This question is about the composition of nuclei.

In the equation $r = r_0A^{1/3}$, $r_0 = 1.41 \times 10^{-15}$ m.

(a) **(i)** State the meaning of

r ....

r_0 ....

A .... [2]

(ii) On Fig. 1.1, sketch a graph to show how r varies with A.

[1]

Fig. 1.1

(b) **(i)** Calculate the radius of the iron-56 ($^{56}_{26}$Fe) nucleus. Give your answer to 3 significant figures.

radius = ... m [2]

(ii) The density of the nucleus of $^{56}_{26}$Fe is 1.44×10^{17} kg m^{-3}.

Show that the mass of a $^{56}_{26}$Fe nucleus is 9.45×10^{-26} kg.

[2]

(c) The ${}^{56}_{26}\mathrm{Fe}$ nucleus is composed of protons and neutrons.

proton mass = 1.673×10^{-27} kg

neutron mass = 1.675×10^{-27} kg

(i) State the number of protons and neutrons in the ${}^{56}_{26}\mathrm{Fe}$ nucleus.

protons ....

neutrons .... [1]

(ii) Calculate the total mass of these protons and neutrons.

mass = ... kg [1]

(d) Use your answers to **(b)(ii)** and **(c)(ii)** to find the difference in mass between the ${}^{56}_{26}\mathrm{Fe}$ nucleus and the total mass of the protons and neutrons of which the nucleus is made.

[1]

(e) Use your answer to **(d)** to calculate the binding energy of the ${}^{56}_{26}\mathrm{Fe}$ nucleus.

binding energy = ... J [2]

[Total: 12]

[Turn over

2 This question is about nuclear fission.

When a uranium-235 ($^{235}_{92}U$) nucleus absorbs a neutron, it becomes uranium-236 ($^{236}_{92}U$) which may undergo fission.

(a) In order to increase the probability of neutron-induced fission, neutrons from a fission reaction are slowed down before they collide with another $^{235}_{92}U$ nucleus. This is achieved by causing the neutrons to collide elastically with other nuclei. Explain why these other nuclei should have a mass which is similar to the neutron mass.

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.... [2]

(b) The fission of $^{236}_{92}U$ can produce many different pairs of nuclei.

Fig. 2.1 shows 3 possible pairs of product nuclei and their relative yields.

nucleus 1	**nucleus 2**	**relative yield**
zirconium-100 ($^{100}_{40}Zr$)	tellurium-135 ($^{135}_{52}Te$)	6.4%
selenium-83 ($^{83}_{34}Se$)	cerium-152 ($^{152}_{58}Ce$)	0.40%
rhodium-110 ($^{110}_{45}Rh$)	silver-121 ($^{121}_{47}Ag$)	0.020%

Fig. 2.1

(i) Write an equation to show the fission reaction which produces $^{110}_{45}Rh$ and $^{121}_{47}Ag$.

[2]

(ii) Use Fig. 2.1 to plot 6 points on Fig. 2.2.

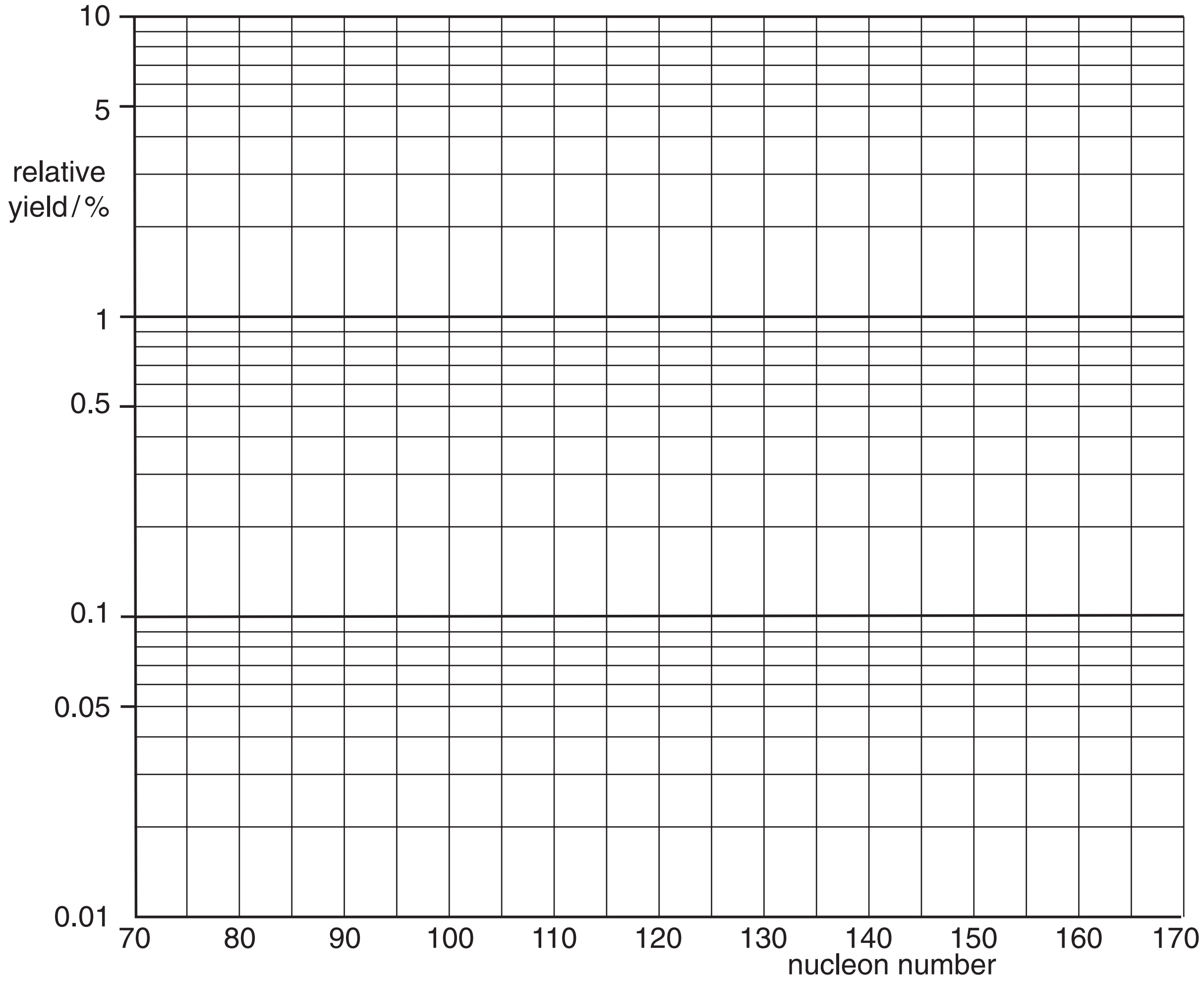

Fig. 2.2

[2]

(iii) On Fig. 2.2, sketch a graph to show how the relative yield varies with nucleon number for **all** the possible fission products. [2]

(iv) Use your graph on Fig. 2.2 to estimate the relative yield of the fission reaction in which a $^{236}_{92}$U nucleus divides into **equal** parts.

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.... [1]

(c) **(i)** All the product nuclei in Fig. 2.1 are β^- emitters.

Write an equation for the β^- decay of $^{121}_{47}$Ag. Use 'X' to represent any new nuclide formed.

[2]

(ii) State the **change** in the number of protons and neutrons which result from a β^- decay.

protons ....

neutrons .... [1]

[Total: 12]

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3 **(a)** Describe briefly the quark model of hadrons.

- Illustrate your answer by referring to the composition of **one** hadron.
- Include in your answer the names of **all** the known quarks.
- Give as much information as you can about **one** particular quark.

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(b) A proton (p^+) can interact with a π^- particle according to the equation

$$p^+ + \pi^- \longrightarrow n^0 + \pi^0 + \pi^- + \mathbf{X}.$$

The charge, baryon number and strangeness of the π^- and π^0 particles are shown in Fig. 3.1.

	charge	baryon number	strangeness
π^-	–1	0	0
π^0	0	0	0

Fig. 3.1

(i) Assuming that strangeness is conserved in this reaction, find the charge, baryon number and strangeness of particle **X**.

charge ....

....

baryon number ....

....

strangeness ....

.... [3]

(ii) Suggest what particle **X** is.

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.... [1]

[Total: 9]

4 This question is about obtaining energy from fusion reactions.

(a) Describe briefly the nature of a plasma.

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.... [1]

(b) Explain how it is possible for a plasma to be confined by a magnetic field.

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.... [3]

(c) Energy may be generated by fusing deuterium nuclei in the reaction

$${}^{2}_{1}\mathrm{H} + {}^{2}_{1}\mathrm{H} \longrightarrow {}^{3}_{2}\mathrm{He} + {}^{1}_{0}\mathrm{n} + \text{energy} \qquad \textbf{reaction 1}$$

The values of binding energy per nucleon for ${}^{2}_{1}\mathrm{H}$ and ${}^{3}_{2}\mathrm{He}$ are given in Fig. 4.1.

nuclide	binding energy per nucleon / MeV
${}^{2}_{1}\mathrm{H}$	1.11
${}^{3}_{2}\mathrm{He}$	2.57

Fig. 4.1

(i) Calculate the energy in joule released in **reaction 1**.

energy = ... J [3]

(ii) Energy may also be generated by the fusion of deuterium and tritium in the reaction

$${}^{2}_{1}\mathrm{H} + {}^{3}_{1}\mathrm{H} \longrightarrow {}^{4}_{2}\mathrm{He} + {}^{1}_{0}\mathrm{n} + \text{energy}$$ **reaction 2**

The amount of energy generated in **reaction 2** is 2.82×10^{-12} J. State why this shows that **reaction 2** is more suitable than **reaction 1** for generating energy.

....

.... [1]

(d) The energy generated in **reaction 2** is shared between the helium-4 nucleus and the neutron.

Calculate what percentage of the energy released is gained by the neutron. Assume that the initial momentum of the products is zero.

percentage = ... % [5]

(e) In a future development of the JET experiment, it is proposed to capture these neutrons outside the confining magnetic field and to convert their energy into a useful form. State **two** facts about the neutrons which make them suitable for this procedure.

1. ....

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2. ....

.... [2]

[Total: 15]

5 **(a)** Describe the principles of operation of the cyclotron.

Your account should describe and explain

- the structure of the cyclotron
- how and where the charged particles gain energy
- why the particles move along a circular path
- why the applied alternating voltage has a constant frequency
- in what ways the cyclotron is similar to the linear accelerator.

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(b) **(i)** An important development in particle physics was the building of an accelerating machine capable of creating a proton-antiproton pair.

Calculate the minimum energy in GeV needed for creating this pair of particles.

energy = ... GeV [3]

(ii) Suggest, without mathematical calculation, why it is not possible to accelerate a particle to this energy using a cyclotron.

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.... [3]

[Total: 15]

[Turn over

6 Neptunium-239 ($^{239}_{93}\text{Np}$) is formed in a fission reactor. This nuclide decays to form plutonium-239 ($^{239}_{94}\text{Pu}$), thus:

$$^{239}_{93}\text{Np} \longrightarrow \, ^{239}_{94}\text{Pu} + \, ^{0}_{-1}\text{e} + \, ^{0}_{0}\bar{\nu}$$

The half-lives are: $^{239}_{93}\text{Np}$: 2.36 days; $^{239}_{94}\text{Pu}$: 24 100 years.

A sample consisting of 3.00 x 10^{20} atoms of $^{239}_{93}\text{Np}$ is isolated and the number of $^{239}_{93}\text{Np}$ nuclei is monitored. This number of nuclei is plotted against time to give the graph labelled Np in Fig. 6.1.

The number of nuclei of $^{239}_{94}\text{Pu}$ is also monitored to give the graph labelled Pu.

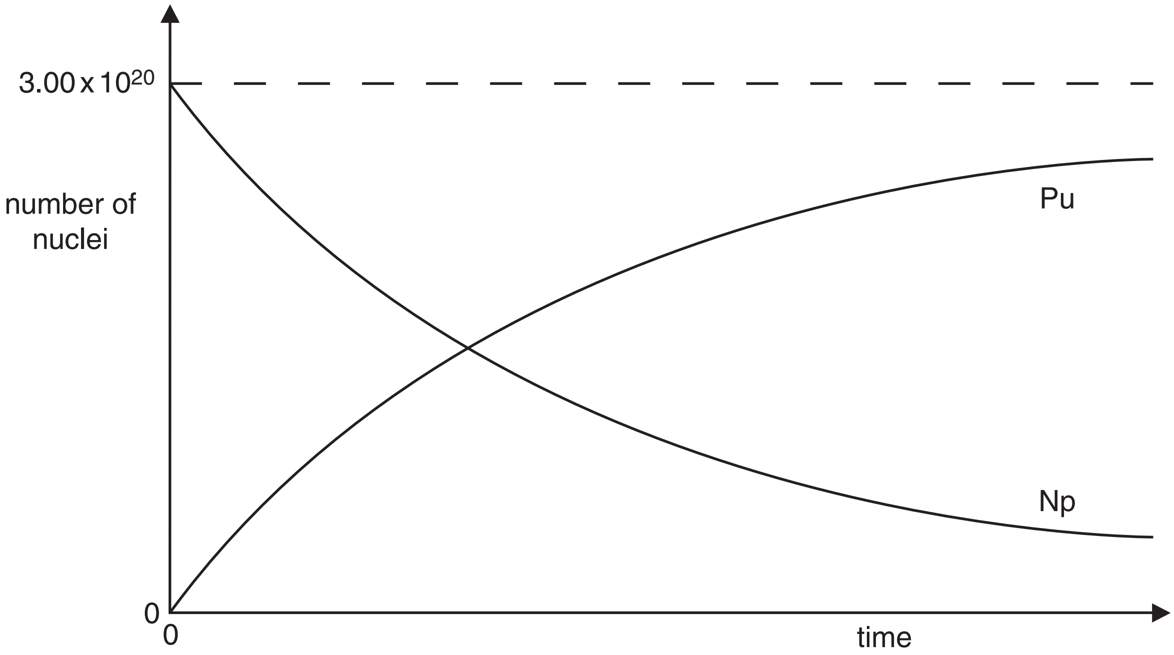

Fig. 6.1

(a) Explain in words the shapes of these graphs.

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.... [3]

(b) Calculate the time taken in days for the number of ${}^{239}_{94}$Pu nuclei to reach 2.70 x 10^{20}.

time = ... days [4]

[Total: 7]

7 Most man-made objects launched into space are satellites placed in a particular orbit around the Earth to function as TV transmitters, telephone relays or weather stations. Some spacecraft, however, have been launched to travel into much deeper space to explore the outer planets of our solar system. All spacecraft, whether satellites or deep space probes, must communicate with Earth by transmitting a radio signal. The circuits producing the signal require battery power and batteries require recharging from an energy source.

Most satellites in orbit around the Earth derive their power from a panel of solar cells which convert sunlight into electrical energy. One such telecommunications satellite transmits a continuous 360 W signal powered from its battery for 24 hours per day. The battery is recharged from a solar panel which has an efficiency of 16% while in direct sunlight of light intensity 1.5 kW m^{-2}.

(a) Suggest what happens to the 84% of light energy which reaches the solar panel but is not converted to electrical energy.

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.... [1]

(b) **(i)** Calculate the minimum surface area of solar panel required to produce the 360 W for the transmitter.

surface area = ... m^2 [2]

(ii) Give **two** reasons why the surface area would have to be much greater than your answer above.

1. ....

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2. ....

.... [2]

For a spacecraft launched into the outer regions of the solar system, it is not practical to have its battery recharged by solar panels. Such spacecraft use a Radioisotope Thermoelectric Generator (RTG). This generator has no moving parts and contains two different metals joined to form a closed electric circuit. When the two junctions between these metals are kept at different temperatures, an electric current is produced. One junction is cooled by space while the other is heated by the decay from a radioactive isotope. RTGs are very reliable sources of power.

Nowadays, RTGs use plutonium-238 which is an alpha emitter with a half-life of 88 years. Each alpha particle is emitted with a kinetic energy of 5.0 MeV.

(c) State **one** reason why solar panels are not practical in deep space.

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.... [1]

(d) Suppose such a spacecraft transmits for 120 minutes each day from a 12 V circuit which draws a current of 5.0 A while transmitting back to Earth. During the rest of the day, the transmitting circuit is shut down. The battery charging, however, carries on continuously.

(i) Show that the energy required per day for transmission is about 0.4 MJ.

[2]

(ii) The overall efficiency in the RTG battery charging system is 25%. Show that the steady power output required from the RTG is about 20 W.

[2]

(iii) Calculate the minimum activity of the source (i.e. the number of 5 MeV alpha particles emitted per second) required to generate this power.

activity = ... Bq [2]

(e) (i) Show that the decay constant λ of Pu-238 is $2.5 \times 10^{-10}\ \text{s}^{-1}$.

[2]

(ii) Calculate the number N of nuclei of Pu-238 required to generate the activity calculated in (d)(iii) .

N = ... [2]

(iii) Calculate the mass of Pu-238 corresponding to this number of nuclei.

mass = ... kg [2]

(f) Plutonium is one of the most dangerous chemical poisons known, as well as being a radioactive hazard. It has been estimated that 1 kg of this substance, suitably distributed, would be enough to kill everyone on Earth. Comment on the risks involved in using plutonium as a fuel for spacecraft.

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.... [2]

[Total: 20]

END OF QUESTION PAPER