(1) The use of nuclear power instead of gas- or coal-fired power stations is being suggested as one way of cutting back emissions of carbon dioxide, which causes global warming.

Assessor's use only

(a) By referring to Albert Einstein's equation, explain the physical basis of nuclear power.

(b) The reaction used in one type of nuclear reactor is:

$$^{239}_{94}\mathrm{Pu} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{142}_{56}\mathrm{Ba} + {}^{93}_{38}\mathrm{Sr} + 5\,{}^{1}_{0}\mathrm{n}$$

The rest masses of the particles involved are:

239 plutonium:	$396.92935 \times 10^{-27}$ kg
142 barium:	$235.64216 \times 10^{-27}$ kg
93 strontium:	$154.27837 \times 10^{-27}$ kg
neutron:	1.67493×10^{-27} kg

In terms of energy production, calculate how many tonnes of coal are equivalent to 1 kg of plutonium. (1 tonne of coal produces 30 GJ of energy.)

(8)

QUESTION TWO: NUCLEAR PHYSICS

Speed of light $= 3.00 \times 10^{8}$ m s^{-1}
Charge on the electron $= -1.60 \times 10^{-19}$ C
1 u $= 1.66 \times 10^{-27}$ kg

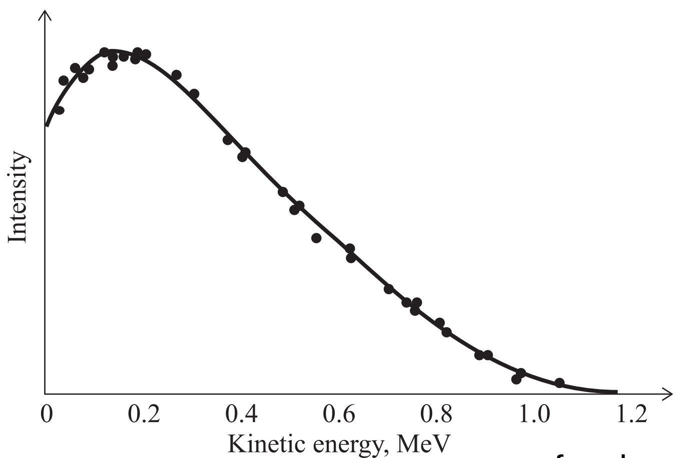
Rest masses:
Rn = 222.017578 u
Ra = 226.025410 u
He = 4.002603 u

A radium nucleus, initially at rest, undergoes alpha decay according to the following:

$$^{226}_{88}\text{Ra} \rightarrow {}^{222}_{86}\text{Rn} + {}^{4}_{2}\text{He}$$

(a) Show that the energy liberated is 4.88 MeV.

(b) Using appropriate conservation laws, calculate the kinetic energy of the alpha particle, and explain why most of the energy released in the decay goes to the lighter particle. Relativistic effects can be ignored.



(c) The graph on the previous page shows the range of kinetic energies observed in the electrons released in a typical beta decay. There is a distribution that cuts off at some maximum kinetic energy. Initially, researchers concluded that the products of beta decay were simply the daughter nucleus and a fast moving electron (beta particle). Wolfgang Pauli used the above graph to conclude that there was some additional particle involved in the beta decay.

Explain how this conclusion can be reached.

(d) The rest mass of a deuteron (one proton, one neutron) is $3.34358372 \times 10^{-27}$ kg. If the proton and neutron are separated, then the sum of the rest masses is $3.34754925 \times 10^{-27}$ kg, i.e., more than the original value. By contrast, if a rocket ship separates itself from a planet by burning fuel to escape the gravitational pull, then the total mass of the rocket on the launch pad is significantly more than the mass of the rocket after escape.

Compare and contrast these situations.

(8)

QUESTION THREE: NUCLEAR EXCHANGES (8 marks)

Surface area of a sphere = $4\pi r^2$
Distance from the Sun to the Earth = 1.50×10^{11} m
The speed of light = 3.00×10^{8} m s^{-1}

(a) Nuclear fission and nuclear fusion are opposite processes, yet each releases energy.

Explain why this is not a contradiction.

(b) Explain why controlled nuclear fusion is difficult to achieve.

(c) Give physical reasons why each of the two statements below is incorrect.

(i) The nucleus of an atom cannot consist of neutrons and protons, because negatively charged particles, much lighter than either neutrons or protons, are often emitted from the nucleus.

(ii) The nucleus of an atom cannot consist of neutrons and protons because protons repel each other, so any nucleus with more than one proton would be unstable.

(d) The Sun loses mass at the rate of 4×10^9 kg s^{-1}.

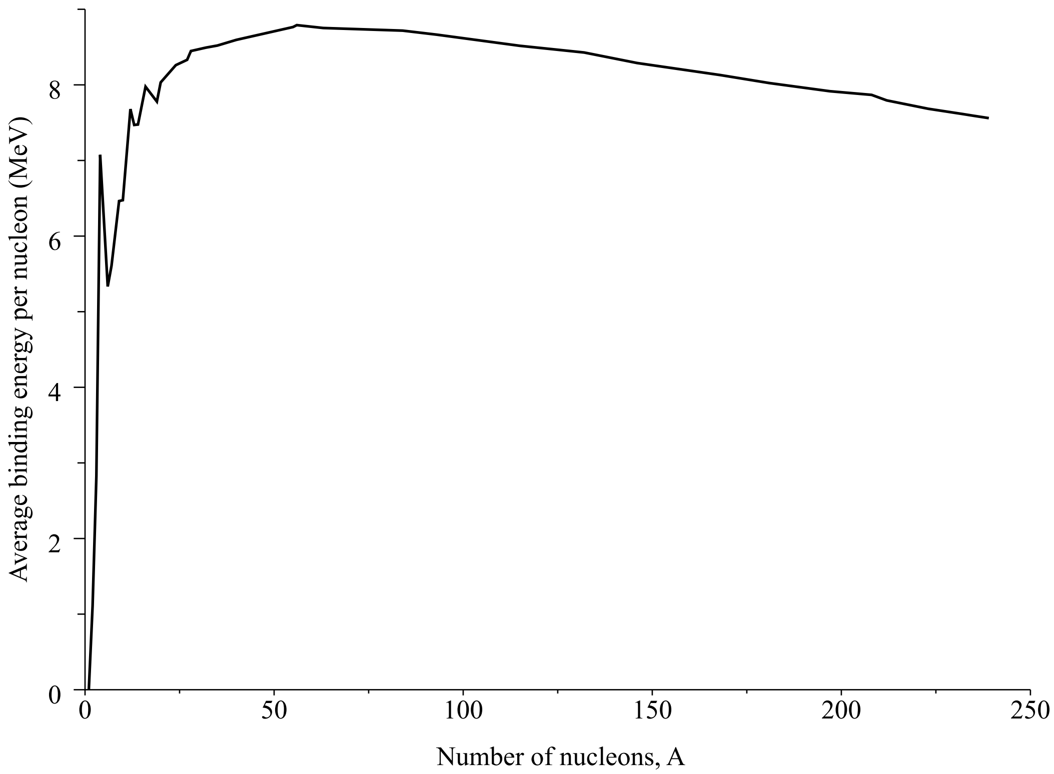
Calculate the site area required for a 1000 MW solar power station on the Earth.

State all assumptions.

(8)

QUESTION FOUR: NUCLEAR AND QUANTUM PHYSICS (8 marks)

Planck's constant = 6.63×10^{-34} J s
Speed of light = 3.00×10^{8} m s^{-1}
Mass of the electron = 9.11×10^{-31} kg
Charge on the electron = -1.60×10^{-19} C



(a) By considering the above graph, discuss the relative stability of nuclei. Reference should be made to physical processes such as fission and fusion, and how the binding energy relates to Albert Einstein's equation $E = \Delta mc^2$.

In 1923, Louis de Broglie stated that, "Because photons have wave and particle characteristics, perhaps all forms of matter have wave as well as particle properties." De Broglie suggested that particles of momentum p should also have wave properties and a wavelength of $\lambda = \frac{\text{h}}{p}$ where λ is the de Broglie wavelength and h is Planck's constant.

(b) Experiments involving electron diffraction show that the de Broglie hypothesis is correct. In one particular experiment a beam of electrons, accelerated by a potential difference $V = 1.00 \times 10^4$ V, is incident on a two-slit barrier with a slit separation of $d = 50.0$ nm.

(i) Find the distance between two adjacent maxima of the diffraction pattern on the screen, which is 1.00 m from the two-slit barrier.

Einstein's special theory of relativity states that the momentum of a particle with velocity, v, changes by the factor $\dfrac{1}{\sqrt{1-\dfrac{v^2}{c^2}}}$.

(ii) Does relativity have a measurable effect on the diffraction result, given that the experimental uncertainty in the distance between maxima is $\pm 5\%$? Explain.

(8)