Cambridge Assessment
International Education

Cambridge Pre-U

PHYSICS **9792/02**

Paper 2 Written Paper **May/June 2022**

INSERT

INSTRUCTIONS
- The question in Section 2 of Paper 2 will relate to the subject matter of the extracts within this insert.
- You will have received a copy of this booklet in advance of the examination.
- The extracts on the following pages are taken from a variety of sources.
- Cambridge International does not necessarily endorse the reasoning expressed by the original authors, some of whom may use unconventional physics terminology and non-SI units.
- You should use all your knowledge of physics when answering the questions.

This document has **8** pages. Any blank pages are indicated.

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Extract 1: The positron – the first anti-particle

In 1928, Paul Dirac published a paper proposing that electrons can have either a positive or a negative charge. This paper did not explicitly predict a new particle but did allow for electrons having either positive or negative energy as solutions. Dirac wrote a follow-up paper that attempted to explain the unavoidable negative-energy solution for the electron. He argued that "... an electron with negative energy moves in an external [electromagnetic] field as though it carries a positive charge." The paper also explored the possibility of the proton actually being a negative-energy electron.

Robert Oppenheimer argued strongly that, if the proton were the negative-energy electron solution to Dirac's equation, the hydrogen atom would rapidly self-destruct. Persuaded by Oppenheimer's argument, Dirac published a paper in 1931 that predicted the existence of an as-yet-unobserved particle that he called an "anti-electron" that would have the same mass as an electron but the opposite charge, and that would mutually annihilate upon contact with an electron.

Carl David Anderson discovered the anti-electron – now called the positron – in 1932, for which he won the Nobel Prize in Physics. The positron was the first evidence of antimatter and was discovered when Anderson allowed cosmic rays to pass through a cloud chamber containing a lead plate. In a cloud chamber, dark tracks are made by streams of droplets condensing on ions produced by a passing alpha-particle or beta-particle, as shown in Fig. E1.1.

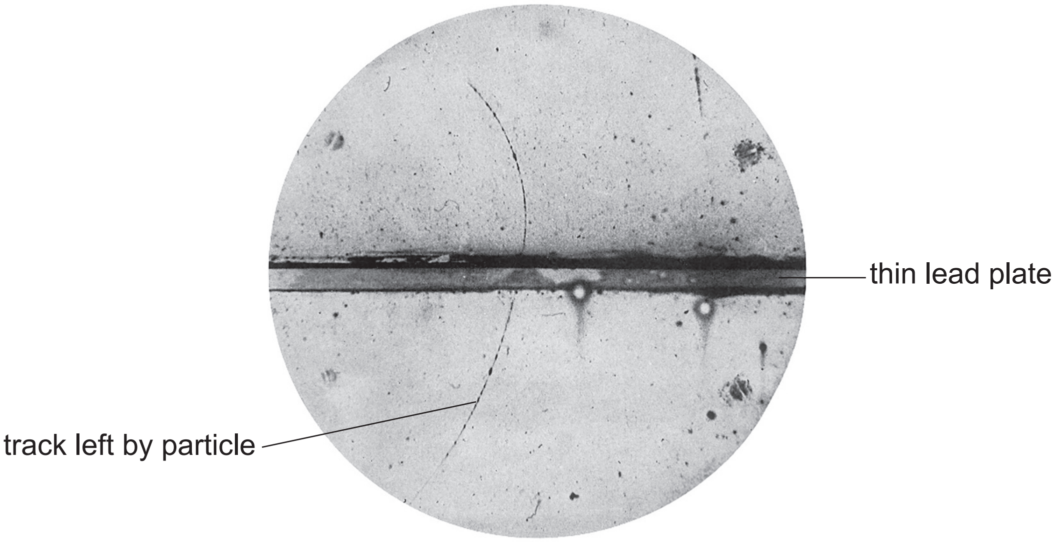

Fig. E1.1

A uniform magnetic field in the whole cloud chamber, perpendicular to the plane of the diagram, made particles travelling in that plane move along tracks which curved according to their mass, electric charge and velocity.

Extract 2: Problems with beta decay

In the early years of the twentieth century, Ernest Rutherford showed that alpha-particles are helium nuclei and beta-particles are electrons. Physicists soon realised that fairly simple changes were taking place in the nuclei of alpha- and beta-emitters, but there were serious problems with the physics in beta-particle emission. The speed, and therefore the kinetic energy, of the emitted charged particles can be found by measuring the curvature of the paths they form in magnetic fields, although very strong magnetic fields are needed in the case of alpha-particles.

When the kinetic energy of alpha-particles emitted by polonium-210 is measured, the spectrum of Fig. E2.1 is obtained. This is exactly what would be expected: each decay liberates the same amount of energy, and conservation of momentum allows only one way for the sharing of this energy. Nearly all the energy is given to the alpha-particles, which all emerge with the same energy of 5.4 MeV.

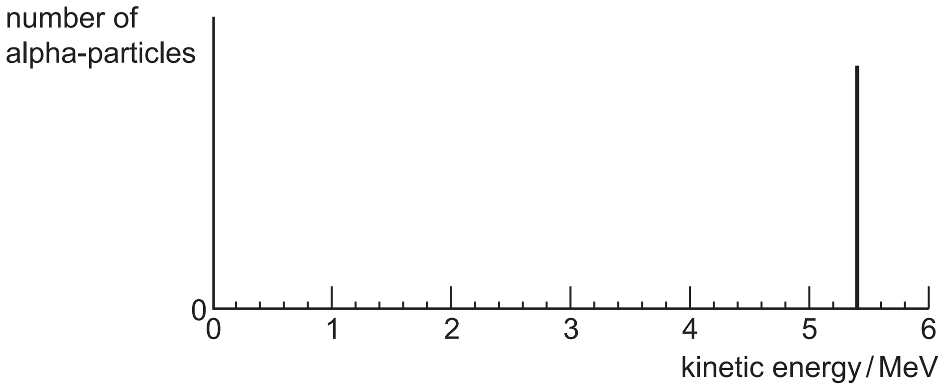

Fig. E2.1

In beta decay, electrons emerge from the nuclei at higher speeds than the alpha-particles produced by alpha decay, but with less kinetic energy. Fig. E2.2 shows the beta-particle energy spectrum obtained when nuclei of bismuth-210 decay. The kinetic energy varies greatly.

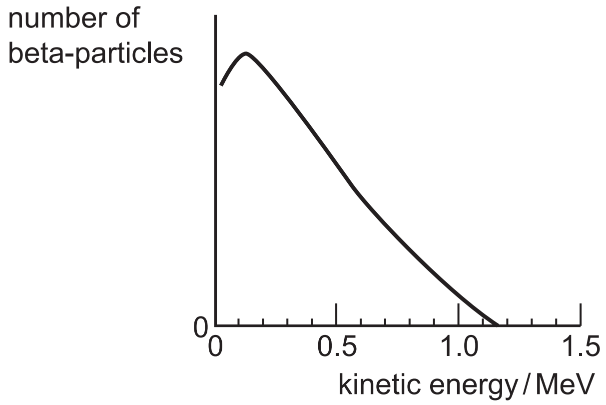

Fig. E2.2

As Fig. E2.2 shows, some beta-particles have an energy of 1.16 MeV, so this should always be the energy released by the process, as with alpha decay. What can have happened to the missing energy for the overwhelming majority of beta-particles, which emerge with less energy? Wolfgang Pauli suggested that the results were exactly what you would expect if there was **another** particle released with the beta-particle. This ‘extra’ particle, for which Enrico Fermi later suggested the Italian name ‘neutrino’, or ‘little neutral one’, would carry off the energy that was missing from the beta-particle.

Extract 3: Detecting the neutrino

During beta decay, the conservation of charge indicates that the extra particle emitted must be uncharged. Secondly, calculation of the rest energies of the parent and daughter nuclei involved, together with the beta-particle's rest energy and 1.16 MeV of kinetic energy, suggested that the rest energy, and hence the mass, of the new particle was very small.

Although neutrinos interact with matter very rarely, Fermi's theory suggested that they could participate in a number of reactions. In 1951 Fred Reines and Clyde Cowan planned to detect antineutrinos, the anti-particles of neutrinos, with the reaction $\overline{\nu} + {}^{1}_{1}\mathrm{p} \longrightarrow {}^{1}_{0}\mathrm{n} + {}^{\;\,0}_{+1}\mathrm{e}$. In this process, an antineutrino produced by nuclear reactions interacts with a proton to produce a neutron and a positron. The positron very soon encounters an electron and they annihilate to give a pair of gamma photons (γ); a few microseconds later, the neutron is absorbed by a suitable heavy nucleus and another gamma photon is emitted. The process is shown in Fig. E3.1.

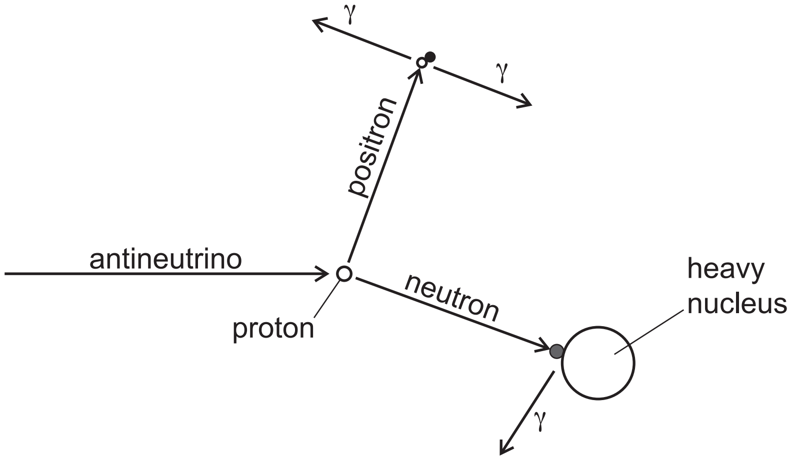

Fig. E3.1 (not to scale)

Reines and Cowan calculated that a nearby nuclear reactor should provide a steady antineutrino flux of 10^{17} antineutrinos $\mathrm{m^{-2}\,s^{-1}}$. They set up their experiment at the Hanford nuclear reactor in 1953. The detector was a tank of water containing a dissolved salt of the heavy metal cadmium, and the gamma photons produced were detected by banks of photomultiplier tubes outside the tank. If a pair of photons were observed travelling in opposite directions, followed by a single photon less than five microseconds later, then this would be convincing evidence that the reaction had taken place.

Unfortunately, there was a large background count, even when the reactor was shut down, due to cosmic rays and to radioactive materials in the environment. This made detection of antineutrinos impossible, so Reines and Cowan moved the detector to the new Savannah River nuclear reactor, which had a well-shielded location for the experiment, 12 metres underground. This greatly improved the signal to noise ratio in the experiment. Despite the low counting rate (about three events per hour), the analysis of these events demonstrated the existence of the antineutrino as a free particle.

Extract 4: The neutrino

The neutrino is a subatomic particle famous for its ability to slip through matter without interacting. Neutrinos have none of the “handles” by which most other particles affect one another: no electric charge, almost zero mass. They are so elusive that a light-year of lead (9.5×10^{12} km) would stop only half of the neutrinos flying through it. The only hope for detecting them is to put a large quantity of matter in one place and hope the occasional neutrino will, by dumb luck, strike an atom somewhere and interact with it. Because so many other radiation sources are releasing energy throughout the Universe, any detector trying to spot neutrinos has to deal with background noise. Picking the signal out of this noise can be a challenge. To make the problem easier, neutrino detectors are built underground, often within deep mineshafts. The rock around the detector blocks any radiation not powerful enough to penetrate beneath the Earth; because neutrinos are so “slippery”, they can pass through the rock and reach the detector device.

Neutrinos are valuable to astronomers precisely because they are so evasive. Since even large thicknesses of matter don’t have much effect, neutrinos can flow right through things which distort or block other types of radiation. For example, our Sun is a ball of hot gases, 1 400 000 kilometres in diameter. Nuclear fusion reactions at the Sun’s core heat these gases, producing vast quantities of energy. We would like to know the details of what’s going on inside the Sun’s core, but the gaseous layers in the way block our view. The gas atoms scatter light so well that a single photon, the basic particle of light, takes many thousands of years to reach the Sun’s surface. Photons leave the core, hit nearby atoms, bounce off them, hit other atoms, and spend centuries doing more and more of the same, until they manage to leak out in the thinner regions near the surface. All that scattering and jostling obscures the details of the interior, just like a bright city skyline looks vague and indistinct when observed through a thick fog. Neutrinos avoid this problem, because they don’t like to interact with the Sun’s atoms. Once nuclear reactions in the core produce neutrinos, they can radiate away and rapidly escape the Sun. Neutrino detectors, then, can tell us what happens deep within the solar core, because they bring us information directly from the source. In the city analogy’s terms, they zip through the fog and reveal the metropolis behind it.

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