OCR
RECOGNISING ACHIEVEMENT

SPECIMEN

Advanced GCE

PHYSICS B (ADVANCING PHYSICS)

G495

Unit G495: Field and Particle Pictures
Advance Notice Article

Specimen

May be opened and given to candidates upon receipt.

INSTRUCTIONS TO CANDIDATES

- Take the article away and read it carefully. Spend some time looking up any technical terms or phrases you do not understand. You are not required to research further the particular topic described in the article.
- For the examination on ……. you will be given a fresh copy of this Advance Notice article, together with a question paper. You will not be able to take your original copy into the examination with you.
- The value of standard physical constants will be given in the Advancing Physics Data, Formulae and Relationships booklet. Any additional data required are given in the appropriate question.

INFORMATION FOR CANDIDATES

- Questions in Section C of Paper G495, Field and Particle Pictures, will refer to material in this Advance Notice.
- Section C will be worth about 40 marks.
- Sections A and B will not be based on the material in the Advance Notice.

This document consists of **6** printed pages and **2** blank pages.

Neutrinos: detecting the undetectable

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 rather 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. 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.

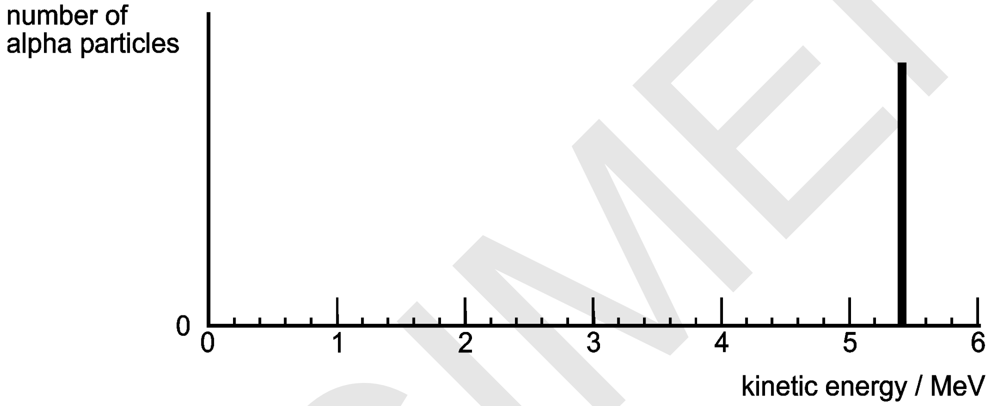

Fig. 1

In beta decay, electrons emerge from the nuclei at higher speeds than the alpha particles produced by alpha decay, but with rather less kinetic energy. Physicists thought that these electrons should all have exactly the same energy as each other, but Fig. 2 shows the beta particle energy spectrum obtained when nuclei of bismuth-210 decay. The energy varies greatly.

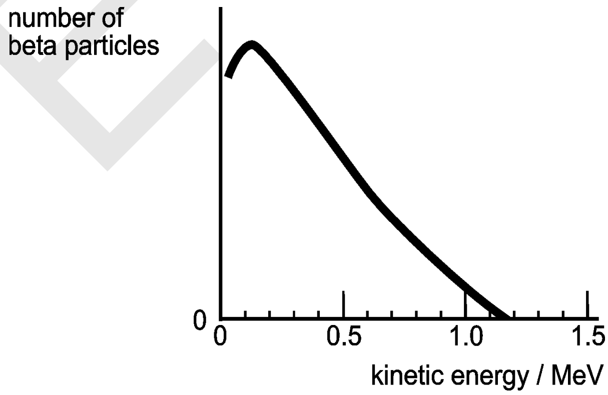

Fig. 2

As Fig. 2 shows, some beta particles have a maximum energy of 1.16 MeV, so this should 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?

‘I’ve done something terrible: I have predicted an undetectable particle’ (W. Pauli)

In 1929, Niels Bohr suggested that the principle of conservation of energy might not hold for beta decay. Most physicists were reluctant to abandon such a fundamental law. In the following year, Wolfgang Pauli wrote a letter to fellow physicists in a conference in Tübingen in Germany, suggesting that that the results were exactly what you would expect if there was **another** particle released with the beta particle. This ‘extra’ particle would carry off the energy that was missing from the beta particle.

What could this new particle be like? First, the conservation of charge indicates that it must be uncharged. Secondly, calculation of the rest energies of the parent and daughter nuclei involved, together with the 1.16 MeV of energy, suggested that the rest energy, and hence the mass, of the new particle was very small. Within three years Enrico Fermi had devised a theory of beta decay incorporating this uncharged particle, for which he proposed the Italian name ‘neutrino’, or ‘little neutral one’. Building a theory around the neutrino, as Fermi did, was one thing: detecting a tiny uncharged particle, as Pauli had already suggested, was quite another matter.

Detecting the neutrino

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 anti-neutrinos, the anti-particles of neutrinos, with the reaction $\bar{\nu} + {}^{1}_{1}\mathrm{p} \rightarrow {}^{1}_{0}\mathrm{n} + {}^{0}_{+1}\mathrm{e}$. In this process, an anti-neutrino 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; 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. 3.

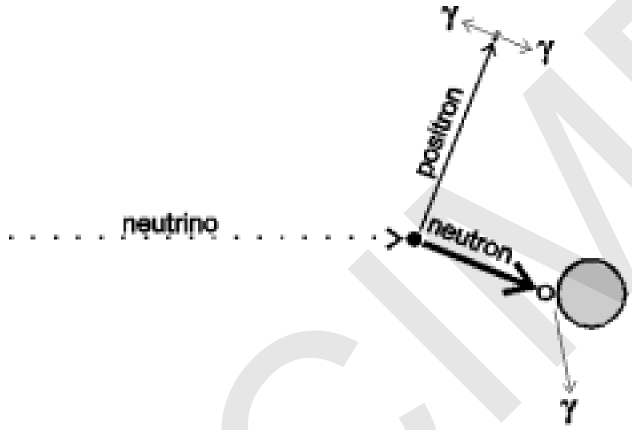

Fig. 3

Reines and Cowan first planned to detect the neutrinos emitted from a nuclear explosion – this was during the 1950s, when atomic bomb tests were a regular occurrence – but they calculated that the more controlled environment of a nuclear reactor should provide a steady anti-neutrino flux of 10^{17} anti-neutrinos m^{-2} s^{-1}. They set up their experiment in 1953, at the Hanford nuclear reactor in Washington State, USA. The detector was a tank of water containing a dissolved salt of the heavy metal cadmium, and the gamma photons produced were detected by 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 mainly to cosmic rays. Clyde Cowan later said, ‘It is easy to shield out the noise men make, but impossible to shut out the cosmos. Neutrons and gamma rays from the reactor, which we had feared most, were stopped in our thick walls of paraffin, borax and lead, but the cosmic ray mesons penetrated gleefully, generating backgrounds in our equipment as they passed or stopped in it. We did record neutrino-like signals, but the cosmic rays with their neutron secondaries generated in our shields were 10 times more abundant.’ This made detection of the anti-neutrinos impossible, so Reines and Cowan moved the detector across the USA to the new Savannah River nuclear reactor on the Georgia/South Carolina border. Like the Hanford reactor, this was a military installation built for the construction of nuclear weapons. This location 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, with the right delay between the gamma photons, finally demonstrated the existence of the neutrino as a free particle.

[Turn Over

Neutrino astronomy and the solar neutrino problem

Having established the existence of neutrinos, the next target was to attempt to detect the neutrinos predicted to emerge from the Sun from fusion reactions such as ${}^{1}_{1}\mathrm{p}+{}^{1}_{1}\mathrm{p}\rightarrow{}^{2}_{1}\mathrm{H}+{}^{0}_{+1}\mathrm{e}+\nu$. The power produced by the Sun is known to be about 4×10^{26} W, from measurements of the energy reaching Earth. This requires the fusion of 6×10^{11} kg of hydrogen each second. As a consequence, the Sun produces about 2×10^{38} neutrinos every second, which means that billions of neutrinos are streaming through your body each second. In medical terms the low reactivity of neutrinos is a blessing, for only a few thousand neutrinos will transfer their energy to you each year, meaning that the absorbed dose is truly negligible. However, this is a considerable disadvantage when you are trying to detect those neutrinos.

A large neutrino detector, containing 400 m^3 of the dry-cleaning fluid tetrachloroethene (C_2Cl_4), was constructed by Ray Davis in 1966 to count the neutrinos coming from the Sun. This was buried nearly 1.5 km underground, in the Homestake Gold Mine in South Dakota, to eliminate background radiation. One in four of the chlorine atoms present in the tetrachloroethene is of the isotope chlorine-37, and this can absorb a neutrino to give a radioactive argon-37 atom. Observing the low count rate of decaying argon-37 atoms is extremely difficult, but over the past 25 years about 12 decays per month have been detected.

Although it was satisfying to have a significant, measurable result, it troubled astro-physicists because it seemed far too low. Two experiments, one in Baksan in the Caucasus Mountains of Russia and one in Gran Sasso in the Italian Appennine mountains, were designed to check and extend the results. These used large detectors made of gallium, which was predicted to react with less energetic neutrinos than chlorine-37. As with the Homestake experiment, these were buried deep underground to screen the apparatus from other ionising radiation. The results confirmed the Dakota results: there were definitely fewer neutrinos detected from the Sun than had been predicted – about a third as many as expected.

Neutrinos, photons and stars

In the core of a star, fusion reactions such as ${}^{1}_{1}\mathrm{p}+{}^{1}_{1}\mathrm{p}\rightarrow{}^{2}_{1}\mathrm{H}+{}^{0}_{+1}\mathrm{e}+\nu$ generate vast numbers of neutrinos. Gamma photons are produced during the reaction and also in the subsequent annihilation of the positrons with electrons in the core. The photons are continually absorbed and re-emitted by the plasma in the stellar core. As the photons travel out, and are absorbed and re-emitted by cooler regions of the Sun, the average energy per photon decreases. As a consequence, the number of such photons increases more than a thousand times as energy travels from the 6 000 000 K core to the 5800 K surface.

Diffusion of molecules of one gas through another is very slow. This is because a moving molecule constantly collides with others, and rebounds in a random direction, as shown in Fig. 4. The average distance between collisions *L* is called the mean free path. After *N* such collisions, an average molecule has had a displacement only $\sqrt{N} \times L$ in magnitude, even though the distance it has travelled is N × L.

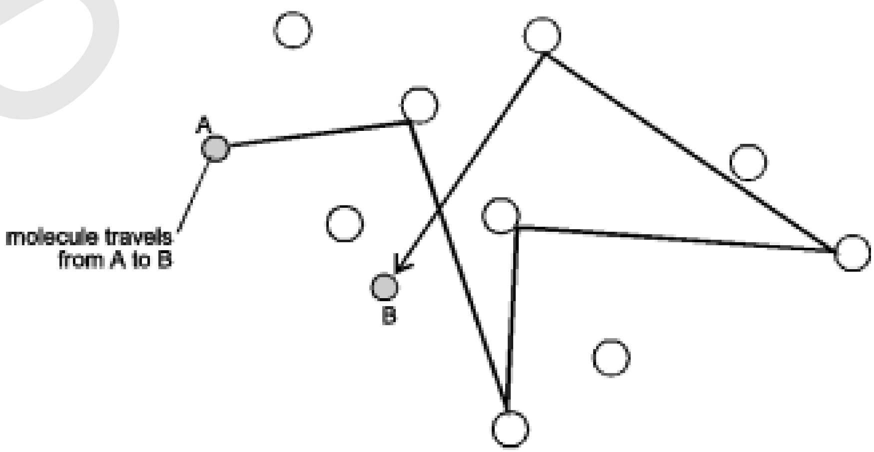

Fig. 4

In very much the same way, the photons take tens of thousands of years to escape from the Sun as they are continually absorbed and re-emitted by ions in the Sun's core, continually changing direction while gradually drifting outwards, as shown in Fig. 5. The neutrinos, generated at the same time, take less than a second to leave the core.

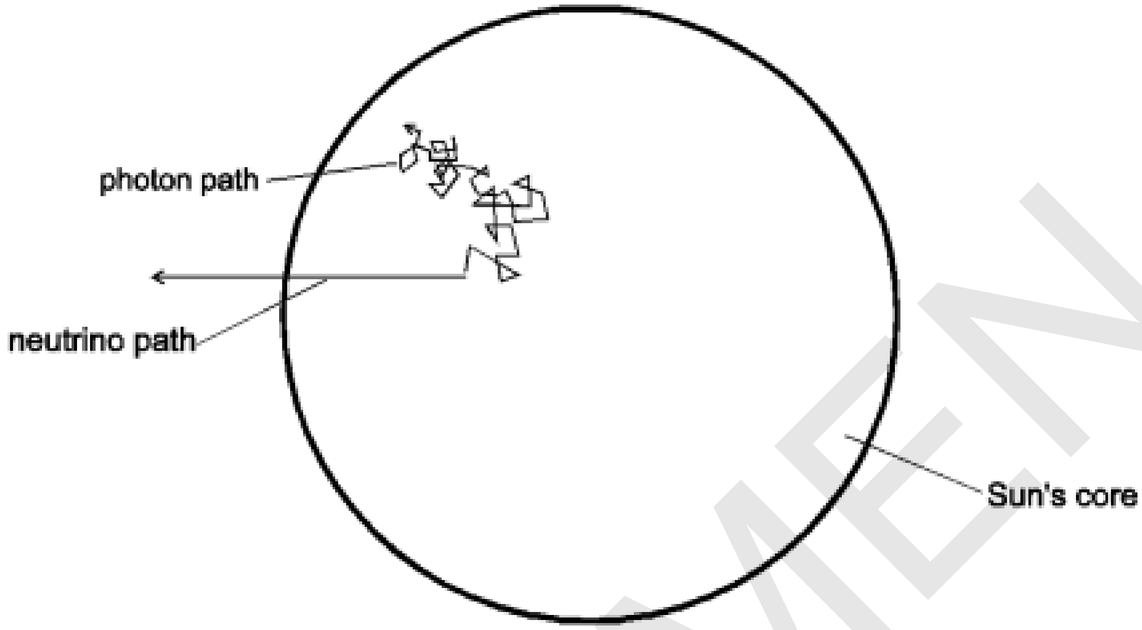

Fig. 5

Fusion in the core of a massive star combines nuclei together until they have all been converted to iron. Then fusion stops, as iron is the most stable nucleus. The star collapses rapidly inwards, creating a supernova. This collapse is predicted to generate an enormous number of neutrinos.

This theoretical fate was dramatically confirmed in February 1987, when a supernova in a neighbouring galaxy, a mere 52 kiloparsecs (170 000 light years) away, was observed. Two hours before any change in the light output had been detected; a burst of 11 neutrinos had been detected in Japan and 8 in the USA. These numbers may seem tiny, but as only about one neutrino in 10^{18} actually interacts with matter, the number detected was consistent with the theoretical prediction for a supernova core collapse at a distance of 52 kiloparsecs from Earth.

End of Article

Reines & Cowan, viz.Reines, Cowan et al 1960 Physical Review 117 159-173

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