RECOGNISING ACHIEVEMENT

OXFORD CAMBRIDGE AND RSA EXAMINATIONS

Advanced GCE

PHYSICS B (ADVANCING PHYSICS) 2865/01

Advances in Physics

JUNE 2004

ADVANCE NOTICE ARTICLE

May be opened and given to candidates upon receipt.

INSTRUCTIONS TO CANDIDATES

- Take the article away and read it through 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 28 June 2004 you will be given a fresh copy of this article, together with a question paper. You will not be able to take your original copy into the examination with you.
- The values 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 A of Paper 2865, Advances in Physics, will refer to this *Advance Notice* article, and may give additional data related to it.
- Section A will be worth about 60 marks
- Section B will consist of two questions. These will ***not*** be based on the *Advance Notice* article. Section B will be worth about 30 marks.
- Four marks are available for the quality of written communication assessed over the whole paper.

This Advance Notice Article consists of 7 printed pages and 1 blank page.

SP (NF/GR) S51789/4

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.

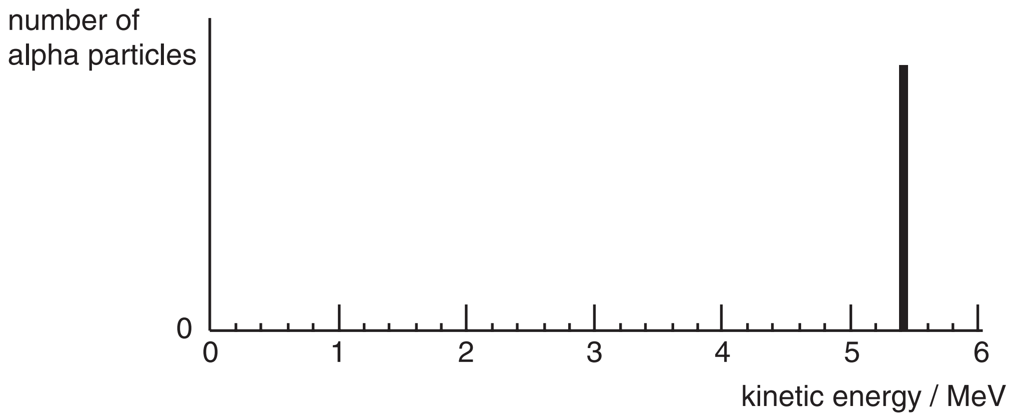

Fig. 1

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.

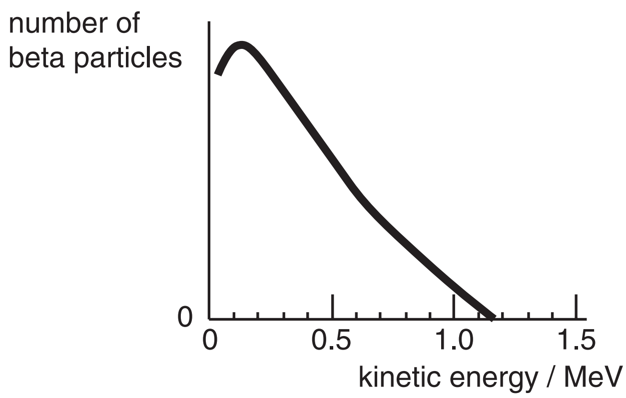

Fig. 2

As Fig. 2 shows, some beta particles have an 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)

Although 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 1930, 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 would carry off the energy that was missing from the beta particle.

What could this new particle be like? Firstly, 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 released, 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 $\overline{\nu} + {}^{1}_{1}\text{p} \rightarrow {}^{1}_{0}\text{n} + {}^{\;\,0}_{+1}\text{e}$. 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.

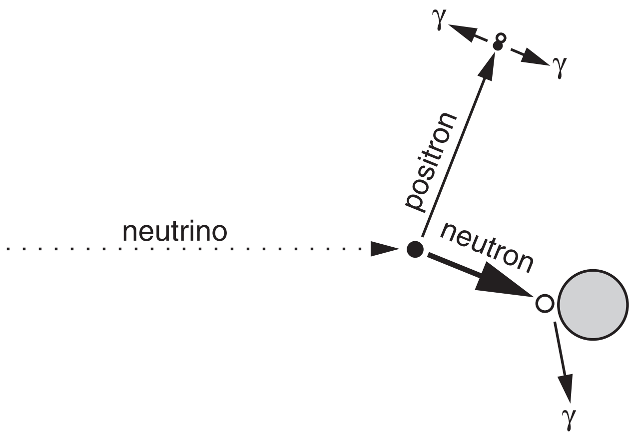

Fig. 3

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 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 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 anti-neutrinos 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 neutrino as a free particle.

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 ${}^{1}_{1}\text{p} + {}^{1}_{1}\text{p} \rightarrow {}^{2}_{1}\text{H} + {}^{\ 0}_{+1}\text{e} + \nu$. 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, it 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 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 as it seemed far too low. Two experiments, one in Russia and one in Italy, 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 far fewer neutrinos detected from the Sun than had been predicted.

Neutrinos, photons and stars

In the core of a star, fusion reactions such as ${}^{1}_{1}\text{p} + {}^{1}_{1}\text{p} \rightarrow {}^{2}_{1}\text{H} + {}^{\ 0}_{+1}\text{e} + \nu$ 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 $\text{N} \times \text{L}$.

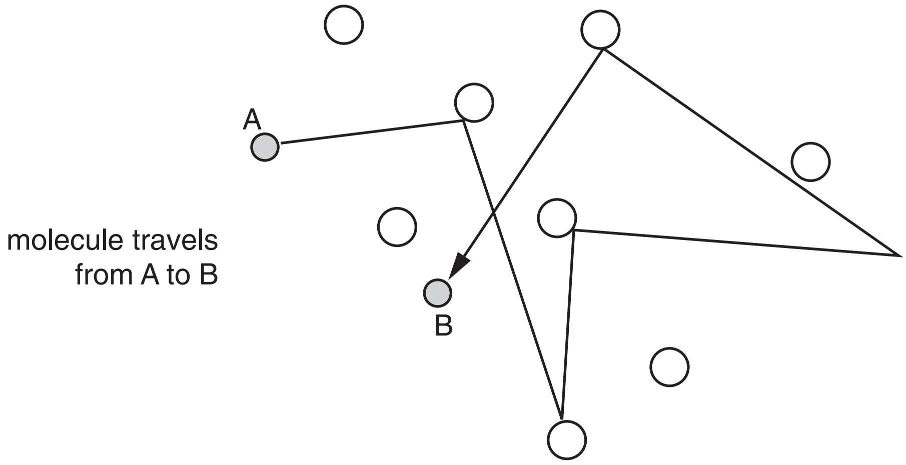

Fig. 4

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.

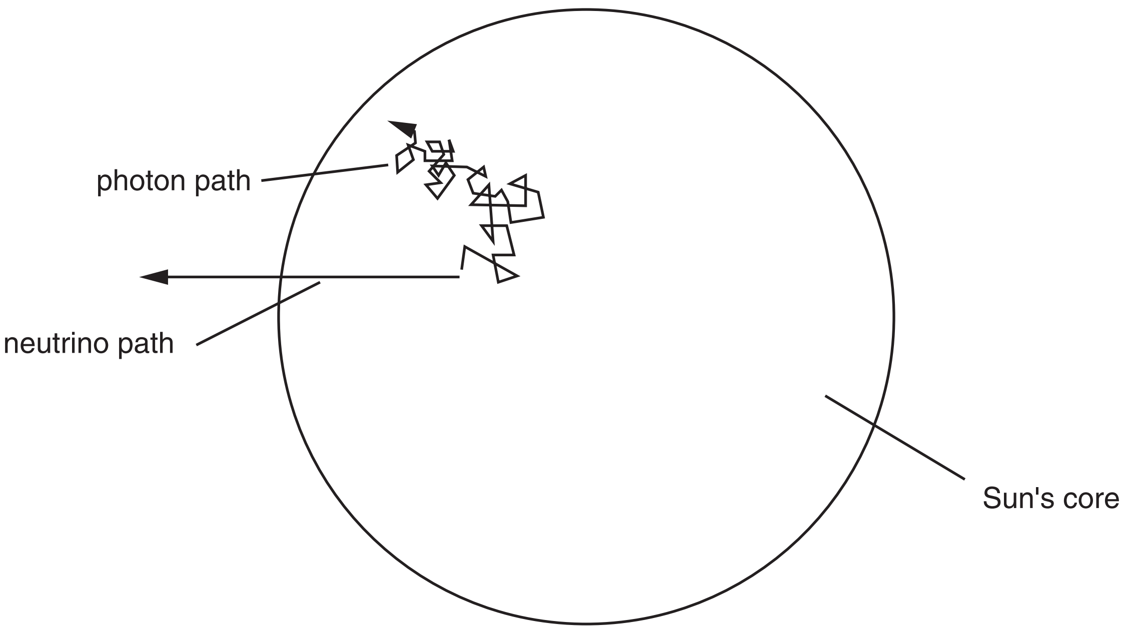

Fig. 5

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.

'Oscillating' neutrinos

Normal matter consists of only a few fundamental particles — two quarks, 'up' and 'down', and two light particles (leptons), the electron and the neutrino. Each of these particles has its anti-particle. However, accelerator experiments have shown that more exotic particles exist at higher energies. First to be discovered were the charmed and strange quarks, heavier versions of the up and down, and the muon, a heavy lepton. Next, the top and bottom quarks and the extremely heavy tau were found. The tau is, in fact, more massive than a proton, but its properties mark it out as a lepton.

Theory predicts that each of these three 'generations' of quarks and leptons should have its own neutrino: the familiar electron-neutrino, the muon-neutrino and the tau-neutrino.

Calculations made after the 1987 supernova showed that the mass of a neutrino could not be more than 3 eV, about $\frac{1}{200\,000}$th of the mass of an electron. This suggests that neutrinos have no mass whatsoever, just like photons. If neutrinos do have mass, however, there is a possible explanation for the solar neutrino problem – neutrinos with mass can theoretically 'oscillate' or change between generations, from electron-neutrinos to muon- or tau-neutrinos. If the electron-neutrinos produced by the Sun were to change to muon-neutrinos or tau-neutrinos on the way, then there would be fewer electron-neutrinos to detect here on Earth.

Two new heavy-water neutrino detectors, one in Sudbury in Canada and one in Kamioka in Japan, are ideally placed to settle the solar neutrino problem. These new detectors are each able to observe the results of different neutrino interactions, which means they can distinguish between the different types of neutrinos. First analyses of data from Sudbury and Kamioka both suggest strongly that the ratio of electron-neutrinos to muon-neutrinos is greater during the day than at night. A possible reason for this is shown in Fig. 6.

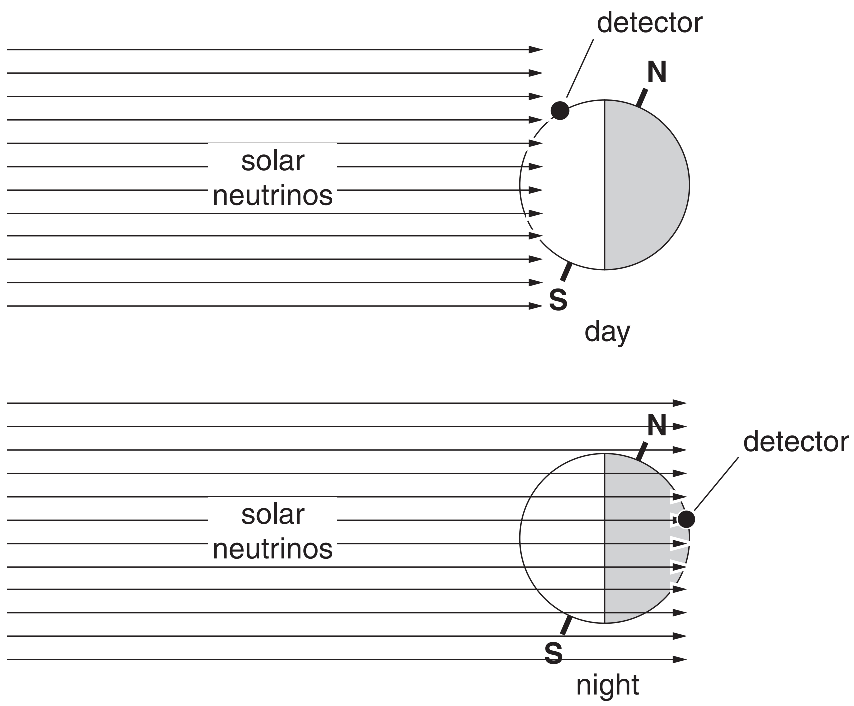

Fig. 6

The neutrinos reaching the detector in the daytime do not have to travel quite so far as those reaching it in the night. This implies that some of the electron-neutrinos have changed into muon-neutrinos during the extra distance they have had to travel through the Earth.

This provides an exciting solution to the solar neutrino problem – the Sun is producing the number of electron-neutrinos predicted by fusion theory, but they are changing into muon-neutrinos, and possibly tau-neutrinos, on the way to us. Although this particular problem now seems to be solved, there are plenty more questions about neutrinos left for physicists to answer.

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