

## Episode 534: Antiparticles and the lepton family

The purpose of this episode is to introduce the lepton family, and also to bring in the idea of antiparticles, which annihilate when they meet particles.

If you have had students research the questions at the end of Episode 533, time must now be allowed for them to feed back what they have found. You may need to supplement their finding with some of the details mentioned below.

### Summary

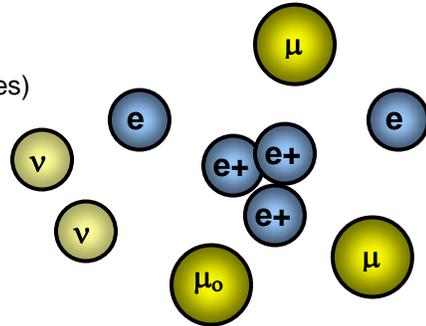
Student presentations: Information about leptons. (15 minutes)

Discussion: PET scans. (10 minutes)

Student activity: Examining particle tracks. (10 minutes)

Discussion: Summarising the main points. (5 minutes)

Student activities: Readings. (20 minutes)



### Student presentations:

#### Information about leptons

Your students should present their findings in response to the questions posed at the end of Episode 533. Important points to establish:

#### Positron $e^+$

Dirac's theoretical prediction of the antiparticle to the electron is too difficult to elaborate here, but Carl Anderson's discovery of it in cosmic rays – he discovered the muon a few years later in the same way – is worth describing.

The original cloud chamber track of Carl Anderson's positron is shown in this famous photograph (Projecting this using a digital projector makes for more dramatic discussion.):

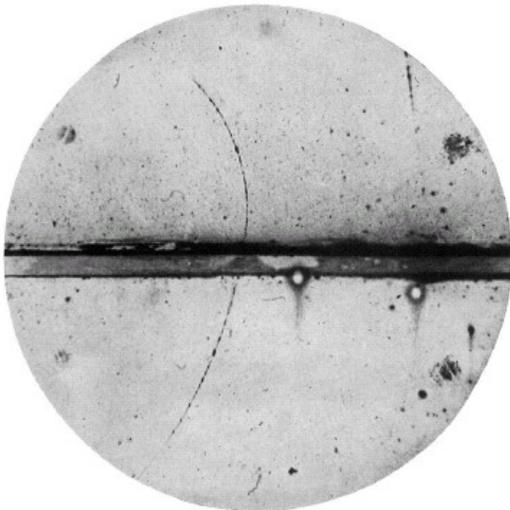


FIG. 1. A 65 million volt positron ( $H_p=2.1 \times 10^6$  gauss-cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ( $H_p=7.5 \times 10^6$  gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

## TAP 534-1: Anderson's positron photograph

The particle is moving up the photograph. It has been slowed down by passing through the lead plate across the centre, and the curvature of the path is caused by a magnetic field. At this stage, it's enough to say that the particle is curved more when it is slower because the particle spends longer in the magnetic field.

Anderson could deduce, from the direction and magnitude of the curvature and the length of the particle track, that the particle was positive and had a mass not more than twice that of an electron.

The positron was the first anti-particle discovered: since then it has been found that every particle has its antiparticle.

## Muon

The muon quote ('Who ordered that?') was from physicist Isadore Rabi – it's whimsically supposed to be the sort of thing you say in a Chinese restaurant when you get some strange dish you don't recognise. The muon was a problem because it had exactly the mass predicted for Yukawa's meson (episode 534), but it didn't undergo strong nuclear interactions at all, which the meson had to do (that was its job, after all!). It turned out to be a heavy type of electron. Like the electron, it has an anti-particle (the anti-muon,  $\mu^+$ ) which is positively charged.

## Neutrinos $\nu$

The problems with beta decay are worth describing in detail. Reactions such as carbon-14  $\rightarrow$  nitrogen-14 +  $\beta^-$  were expected to produce beta particles with identical kinetic energy: this is what happens in alpha decay. This does not happen in beta decay; sometimes a lot of the energy seems to be missing.

In 1930 Wolfgang Pauli suggested, in a famous letter to fellow physicists starting 'Dear Radioactive Ladies and Gentlemen', in which he wrote 'I've done something terrible: I have predicted an undetectable particle'. He suggested that the 'lost' energy was carried away by a new particle, which must be chargeless and have virtually no mass. Enrico Fermi developed the theory of this new particle, which he called a neutrino, but it wasn't until 1951 that Reines and Cowan discovered it at the Savannah River nuclear reactor. Current (2005) thought is that the mass of the electron neutrino is in the range  $0 < \text{mass} < 3 \text{ eV}/c^2$  (compare with the electron,  $m_e = 0.511 \text{ MeV}/c^2$ ).

Like the electron and the muon, neutrinos have antiparticles. Furthermore, there are different neutrinos associated with the electron and the muon.

Because these light particles do not experience the **strong force** of hadrons, they form a different category of particle and given the name **leptons**.

There are now a total of 12 leptons: the electron, the muon, and a super-heavy version called the tau ( $\tau$ ); a neutrino for each of these three; and six antiparticles for these six particles. The six leptons each have a lepton number of +1, while the six anti-leptons each have a lepton number of -1.

## Discussion:

### PET scans

Take a look at PET scans and how they are made.

When a positron meets an electron, they annihilate to produce a pair of gamma ray photons, each of energy 511 keV. (Both the electron and the positron have a mass of  $511 \text{ keV}/c^2$ .) This principle is used in medicine, in Positron-Electron Tomography (PET) scans. A radiochemical emitting positrons is injected into the body. When the chemical reaches the organ of interest, positrons emitted very soon meet electrons and annihilate. The scan reveals exactly where the radiochemical is by looking for a pair of gamma photons travelling in opposite directions.

You may like to ask students how they think radiochemicals which emit positrons are made: they can be led to realise that the unstable nuclei lose positive charge when a positron is emitted, and so have too many protons. This suggests that you have to fire protons into the nucleus, which is one way this is actually done.

TAP 534-2: Making PET scans

## Student activity:

### Examining particle tracks

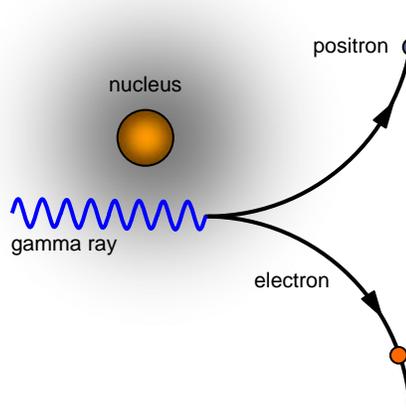
Examining particle tracks: This can be done as class discussion with a digital projector, as suggested for the Anderson photograph of the positron track shown above, or students can work individually or in pairs, using printed copies of the images or looking at them on computer screens. If you adopt the latter approach, give a little more time for the activity: it could be a homework activity. The questions are intended for students late in the Post-16 level course, so you should concentrate on simple patterns:

Gamma photons are not very ionising, so tend not to leave tracks in bubble chambers or cloud chambers.

Gamma photons of enough energy ( $2 \times 511 \text{ keV}$ ) can produce an electron-positron pair (provided they are near nuclei at the time: don't emphasise this point)

Particles and anti-particles – protons and antiprotons in this case – can annihilate with production of energy, and also 'new' mass in the case of big particles

In a magnetic field, charged particles follow curved paths, with opposite charges curving in opposite directions



TAP 519-3: Particle tracks

TAP 534-3: Annihilation and pair production: Bubble chamber pictures

## **Discussion:**

### **Summarising the main points**

Establish the main points of this episode:

The electron is one of a small family of fundamental particles called leptons, which are quite different from the nuclear particles (hadrons) of Episode 533.

Particles have anti-particles, with opposite value of charge, lepton number and (by implication) baryon number and strangeness as well).

## **Student activities:**

### **Readings**

Here are a number of supplementary readings that you may care to use to broaden students' background knowledge:

The discovery of beta decay.

TAP 534-5: The discovery of beta decay

Three poems about particles.

TAP 534-6: Three poems about particles

Tracking particles.

TAP 519-3: Particle tracks

## TAP 534- 1: Anderson's positron photograph

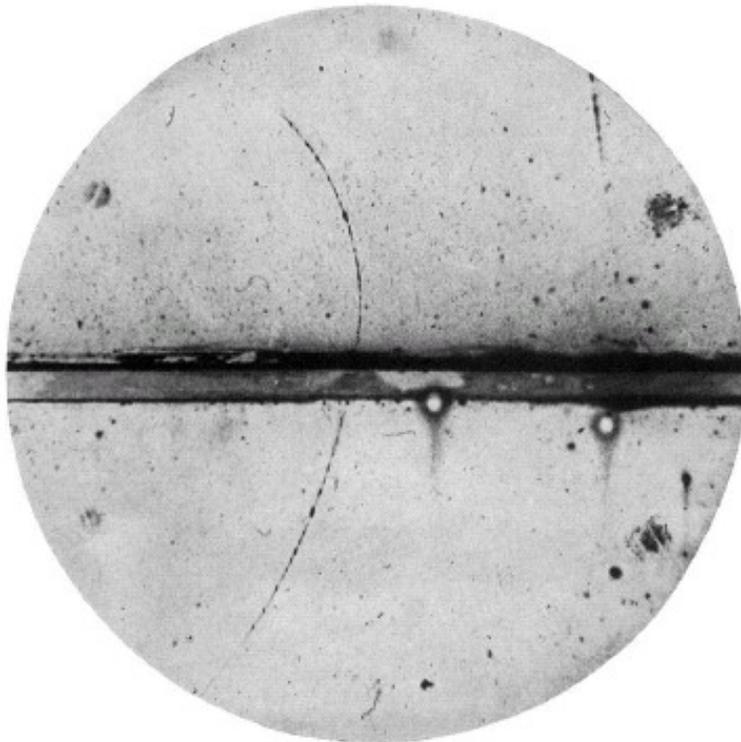


FIG. 1. A 63 million volt positron ( $H_p = 2.1 \times 10^6$  gauss-cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ( $H_p = 7.5 \times 10^4$  gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

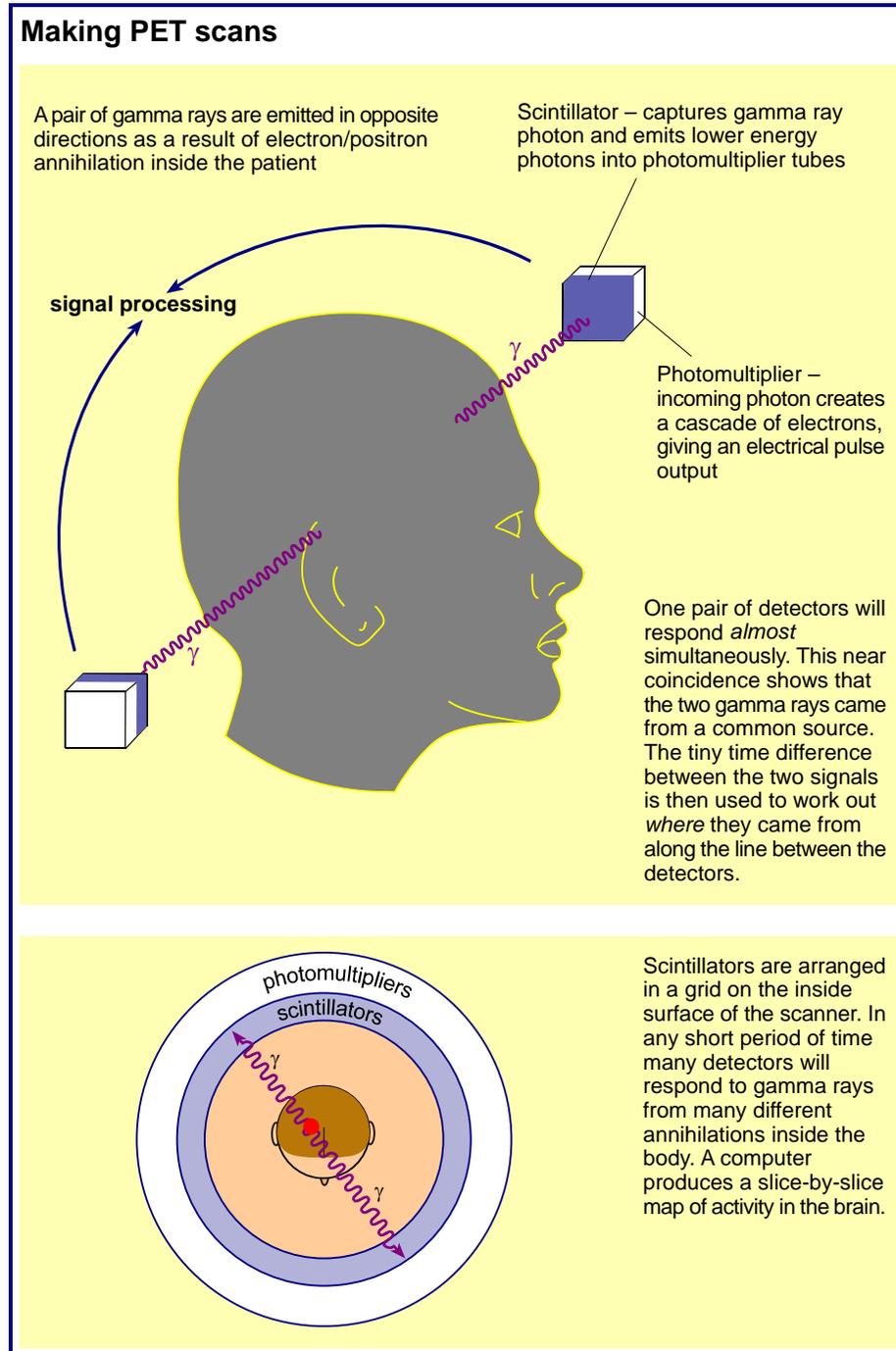
“On August 2 1932 during the course of photographing cosmic-ray tracks produced in a vertical Wilson chamber (magnetic field 15,000 gauss) designed in the summer of 1930 by Prof R A Millikan and the writer the track shown in fig 1 was obtained which seemed to be interpretable only on the basis of a particle carrying a positive charge but having the same mass of the same order of magnitude as that normally possessed by a free electron”.

## **External reference**

The original reference is:

Anderson Carl D, The positive electron, Physical Review, Vol 43 pp 491-494 15 March 1933

## TAP 534- 2: Making PET scans



**Practical advice**

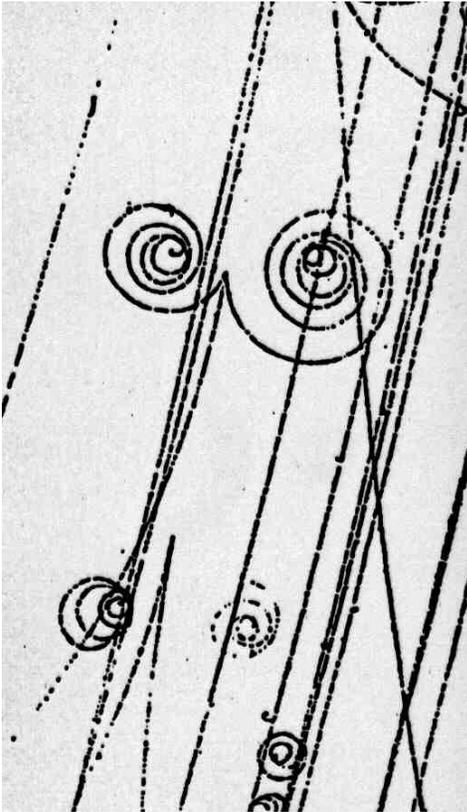
This diagram is reproduced here so that you can discuss it with your class.

**External reference**

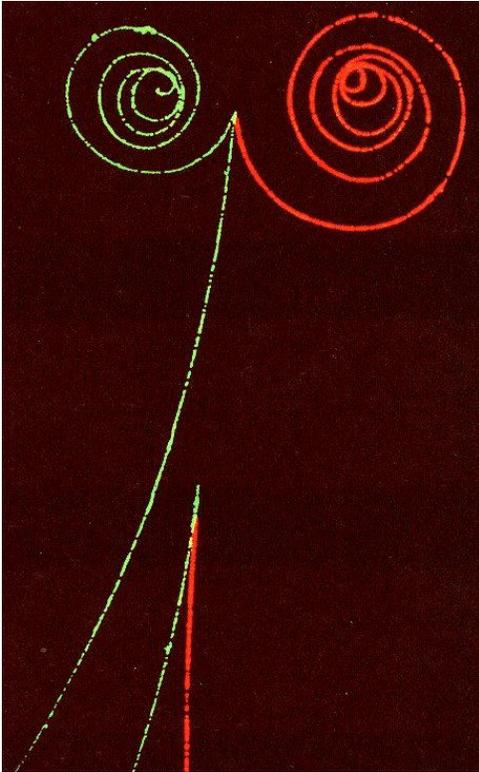
This activity is taken from Advancing Physics chapter 17, 200

### TAP 534- 3: Annihilation and pair production: bubble chamber pictures

Pair production: The original image



A processed image, with some tracks removed, and (below) the tracks coloured by curvature:



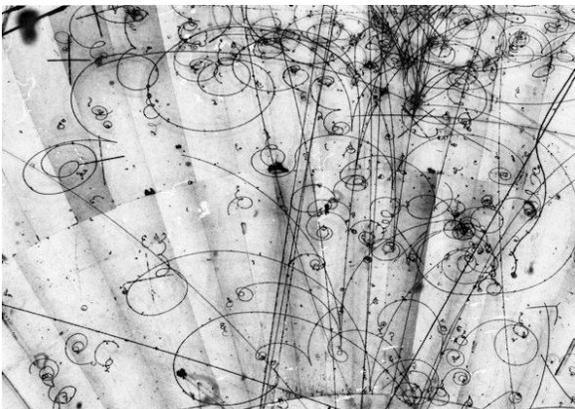
Both images can be interpreted by assuming two photons to be entering from the top of picture, leaving no track. One (top) has created a positron / electron pair and a 'knock on' electron from within an atom. The other has simply produced a positron / electron pair.

To think about:

- is there a minimum photon energy required to produce a positron / electron pair?

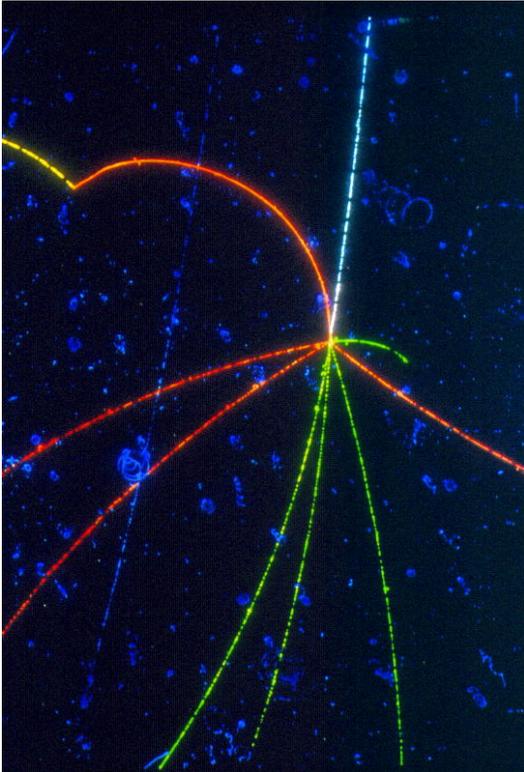
The pair produced in the lower event carry considerably more kinetic energy than the upper pair:

- what feature of the picture shows this?
- what is the physical reason for this?



This image above shows pair production of electrons and positrons as a stream of photons enters a bubble chamber. The photons leave no track, so that the particles appear to come from nowhere. How many of these events can you identify?

### Proton–antiproton annihilation



Here an antiproton (coming in from the bottom left) strikes a proton. Mutual annihilation leads to four pairs of pions ( $\pi^+$  and  $\pi^-$ ). These curve in opposite directions in the magnetic field.

To think about:

- the antiproton is being deflected slightly to the right. In which plane is the magnetic field?
- can you identify the  $\pi^+$  and  $\pi^-$  particle tracks?

## Practical advice

These pictures may be used to illustrate annihilation and pair production. They might be printed out or made into OHP transparencies, with suitable captions. Use the questions as you see fit.

## Answers and worked solutions

### Pair production

The minimum photon energy required to produce a positron / electron pair is  $2mc^2$ .

The feature that shows higher speed is less curvature.

Initial photon had greater energy.

### Proton–antiproton annihilation

The magnetic field is directed “into the page” (NB anti-proton has a negative charge)

The  $\pi^+$  and  $\pi^-$  particle tracks are red and green respectively (the  $\pi^-$  will deflect the same way as the anti-proton)

### External reference

This activity is taken from Advancing Physics chapter 17, display material 10S

## TAP 534- 5: The discovery of beta decay

This reading is about an important discovery made in the early days of the study of radioactivity. It involves many of the most famous nuclear scientists of the day and led to an amazingly bold prediction of the existence of a small neutral particle, eventually called the neutrino. The theory also meant that physicists had discovered a hitherto unknown force in nature – the weak force.

Radioactivity – the emission of mysterious ‘rays’ from certain rare elements – was discovered in 1896 by the French physicist Henri Becquerel. The emissions were soon classified in terms of how penetrating they were as alpha, beta and gamma rays. The alpha rays – soon found to be massive particles, helium nuclei – left a particular source with a definite kinetic energy that was a characteristic identifier of the source. In the early days it was assumed that beta rays, identified as high-speed electrons, also left the source with a characteristic energy. Indeed early experiments carried out between 1907 and 1914 seemed to confirm this assumption. But they were wrong: the detection relied on photographic techniques that were too insensitive to reveal that some beta particles from a particular source had less energy than others.

### Constant energy produces a line spectrum

Early experimenters were looking for patterns in the outputs of the various radioactive elements that were being discovered. It was possible to identify elements from the spectrum of the light they gave out when heated. It should be possible to do much the same for radioactive sources using these newer emissions. What they were beginning to realise at this time was that a good emitter like radium was changing into other radioactive elements with each emission, and it would be nice to be able to identify these from the emission they gave out. To start with it had been thought that the new elements were all forms of the original source, and they were named radium B, radium C, radium D, uranium X, etc. The idea that elements could change was against all the beliefs about atoms and elements so carefully built up in the nineteenth century.

The energy of beta particles was found by making them move through a strong magnetic field before landing on a photographic plate. The slower less energetic ones were deviated more. These experiments showed that many beta emitters produced definite lines on the plate, where betas with a particular speed congregated. But the line spectra produced were ‘messy’. For some emitters it was hard to detect the betas with a discrete and definite energy against the noisy background in the exposed plates. In Berlin, Lise Meitner and Otto Hahn were two of several scientists across Europe investigating this problem. Remember that nobody realised that all these effects were due to changes in the nucleus – the nucleus had not then been discovered.

The worst of all the emitters investigated by Meitner and Hahn was named radium E, which we now know is a radioactive isotope of bismuth ( $^{210}\text{Bi}$ ). In 1911 Otto Hahn (with Lise Meitner, one of the discoverers of nuclear fission – but that was yet to come) wrote to Ernest Rutherford:

RaE is the worst of all. We can only obtain a fairly broad band. We formerly thought that it was as narrow as the other bands [as found in other emitters], but that is not true. It looks as if secondary ... effects had a maximum influence on rays of a medium velocity like RaE.

Hahn was thinking that there might be some secondary process inside the atom which somehow altered the energy distribution and smoothed things out, especially effective with low-energy (soft) beta rays. Then later:

The trouble with the soft rays [from RaE] is very great and we do not feel sure that we can overpass the difficulties to obtain good lines.

But even the great Rutherford at this time was not too worried, and replied:

The continuous  $\beta$ -ray spectrum observed for uranium X and radium E may be ultimately resolved for a number of lines.

The problem was that there were two effects happening at the same time. Electrons from beta decay do always produce a continuous spectrum – the vital fact that was to lead to so much. But several beta emitting nuclei also emit gamma rays, which like alpha particles have single definite energies. These gamma rays can then give their energy to an electron in the outer part of the atom, knocking it out of the atom so that it looks like a beta particle from the nucleus, but one with a single definite energy. It was too attractive to physicists looking for a pattern to put more emphasis on the nice line spectra than on the vague and inexplicable continuous one. And when such lines occurred they were much easier to see on the photographic plates used than was the vaguely darkened background due to the continuous spectrum. Remember also that sharp line spectra were what physicists expected to see; that was what they were used to, and what theory told them ought to happen. So they saw what they expected.

### **Why is a continuous energy spectrum a problem?**

So what was so important about the continuous spectrum anyway? It is always annoying for a scientist or a detective to discover that the interesting clues they are looking for are in fact far less important than the messy stuff that just seems to get in the way. But as the evidence for a continuous range of energies being carried away from a radioactive source grew, the very small numbers of what were to be called 'nuclear physicists' began to get more and more worried. The decisive evidence was coming not from hard-to-read photographic plates but from the new generation of detectors using an electrical discharge produced by the ionising radiations. In April 1914 a young 23-year-old physicist called James Chadwick was given a scholarship to do research and chose to join Hans Geiger in Berlin. Using a primitive form of what was later to be called a Geiger counter Chadwick obtained clear evidence for the continuous spectrum of beta particle energies – and not just with radium E. Chadwick was to become famous in 1932 for discovering the neutron, but choosing to go to Berlin in 1914 was not one of his better ideas. He spent the war years in an internment camp.

### **Is the law of conservation of energy true?**

This was the question raised by the continuous spectrum of beta particle energies. To avoid answering the question with a 'NO!', physicists had to postulate a completely new particle that had no charge and negligible or zero mass. It was not shown experimentally to exist until 1956, and required a new fundamental force in nature to explain it.

The problem was simple: if some beta particles leave a nucleus with less energy than others, what has happened to the 'missing' energy? It was seriously considered in the 1920s that maybe the law of conservation of energy just didn't apply to the strange world of the quantum and the relativistic equivalence of mass and energy. In 1930 the distinguished physicist Niels Bohr said in a lecture:

At the present stage of atomic theory we have no argument, either empirical or theoretical, for upholding the energy principle in  $\beta$ -ray disintegrations, and are even led to complications and difficulties in trying to do so.

Then the rather eccentric Austrian physicist Wolfgang Pauli came to the rescue with a very brave idea indeed. In December 1930 he wrote a letter to a meeting of physicists at Tübingen University:

Dear radioactive ladies and gentlemen,

I have come upon a desperate way out regarding ... [some fairly obscure data], as well as to the continuous  $\beta$ -spectrum, in order to save .... The energy law. To wit, the possibility that there could exist in the nucleus electrically neutral particles, which I shall call neutrons, which have spin  $\frac{1}{2}$  and satisfy the exclusion principle and which are further distinct from light-quanta in that they do not move with light velocity. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any case not larger than 0.01 times the proton mass. ... The

continuous  $\beta$ -spectrum would then become understandable from the assumption that in  $\beta$ -decay a neutron is emitted along with the electron, in such a way that the sum of the energies of the neutron and the electron is constant.

Some theoretical calculations pointed to Pauli's neutral particle having zero rest mass. The word neutron seemed to too big for such a tiny, if important, object. The Italian physicist Enrico Fermi started calling it the little neutral one – or neutrino. This became the accepted name when in 1932 Chadwick discovered a much larger neutral component of the nucleus that better deserved to be called the neutron.

### **Practical advice**

This reading is designed as an extra to support the episode. It adds some personal context to the hard to accept discovery of the continuous energy spectrum associated with beta decay. It is interesting that one of the first challenges thrown up by the comparatively simple observation of a continuous beta energy spectrum should throw doubt on one of the most fundamental laws in physics, the conservation of energy.

### **Social and human context**

The problem of the continuous beta spectrum shows how even the greatest physicists of the day were confused by what was being discovered, and found it hard to accept. When the observations were accepted they seemed to shake one of the most basic laws of physics.

### **External reference**

This activity is taken from Advancing Physics chapter 17, 10T

## TAP 534- 6: Three poems about particles

For many centuries, scientific ideas have inspired poets with raw material. These poems all deal with elementary particles, portraying everyday experiences and commenting on the scientific imagination.

### **Cosmic Gall**

Neutrinos, they are very small.  
They have no charge and have no mass  
And do not interact at all.  
The earth is just a silly ball  
To them, through which they simply pass,  
Like dust maids down a drafty hall  
Or photons through a sheet of glass.  
They snub the most exquisite gas,  
Ignore the most substantial wall,  
Cold-shoulder steel and sounding brass,  
Insult the stallion in his stall,  
And, scorning barriers of class,  
Infiltrate you and me! Like tall  
And painless guillotines they fall  
Down through our heads into the grass.  
At night, they enter at Nepal  
And pierce the lover and his lass  
From underneath the bed – you call  
It wonderful; I call it crass.

by John Updike

From: John Updike 1964 *Telephone Poles and Other Poems* (London: Andre Deutsch)

### **Nomad**

The particle scientist  
is more or less  
happy. He has no home.

All his ladders  
go straight down

and claim the nameless.

by Anthony Piccione

From: Anthony Piccione 1977 *Anchor Dragging Poems* (BOA Editions)

### **Little Cosmic Dust Poem**

Out of the debris of dying stars,  
this rain of particles  
that waters the waste with brightness;

the sea-wave of atoms hurrying home,  
collapse of the giant,  
unstable guest who cannot stay;

the sun's heart reddens and expands,  
his might aspiration is lasting,  
as the shell of his substance  
one day will be with frost.

In the radiant fields of Orion  
great hordes of stars are forming,  
just as we see every night, fiery and faithful to the end.

Out of the cold and fleeing dust  
that is never and always,  
the silence and the waste to come –

this arm, this hand,  
my voice, your face, this love.

by John Haines

From Bonnie Bilyeu Gordon 1985 *Songs From Unsung Worlds* (Boston, MA: Birkhauser)

## **Practical advice**

Each in their own way, these poets reflect on the success of the scientific imagination. Is their aim to grasp the incredible ideas better through the language of poetry? Certainly they link astronomical and nuclear scales to the human scale of reality.

## **External references**

This activity is taken from Advancing Physics chapter 17, 20T

These poems, and many others inspired by science, are published in:

Carey J (ed.) 1995 The Faber Book of Science (London: Faber & Faber)

Ferris T (ed.) 1991 The World Treasury of Physics, Astronomy and Mathematics (Boston, MA: Little, Brown)