**The Neutrino**

Let’s kick off with what the syllabus wants us to know about the neutrino:

* Radioactive decay resulting in two particles.
* If momentum is not conserved, a third particle (neutrino) must be present.

Now that’s just not good enough. It doesn’t do justice to one of the most enigmatic particles in out universe. I’m pretty sure we can do better than that.

I’m certainly going to try.

It’s a very, very strange world out there.

To help us get some sort of picture of what is out there, I am going to have to break this talk up into a series of shorter talks, which for reasons which will soon become clear, I will call ‘Crazytalks’.

Our story begins with the phenomenon known as Beta Decay.

**Crazytalk Number One**

In Beta Decay, a neutron breaks up in to a proton plus an electron.

The equation is n0 → p+ + e-

You see it turns out that some atomic nuclei are unstable and decay to form other types of more stable atoms. These are called radioactive nuclei and in some cases they emit an electron when they decay.

Now I readily admit that that is just a crazy thing to say, but welcome to the world of quantum physics; it’s a crazy place. In fact we now know that what actually happens is that a neutron in the nucleus of the original atom decays into a proton and an electron. The proton stays put while the electron gets kicked out.

But for now we’re going to ignore the silliness of that statement and just accept that it’s true (I do hope to come back to that particular silliness in another podcast).

However when scientists investigated the momentum of the particles before and after this reaction, they noticed something strange.

The momentum of the particles *produced* by the reaction was less than the momentum of the neutron *beforehand*, yet the law of *conservation* of momentum (which is only one of the foundation stones of *all* Physics) tells us that the momentum before and after must be the same.

Yet no matter how many times the experiment was repeated scientists got the same result.

They had a problem.

Maybe some sort of timeline will help us set the context here.

1896: Henri Becquerel discovered some strange radiation coming from uranium salts.

1899: The New Zealander Ernest Rutherford showed that there are *two* different types of radiation, which he called alpha and beta (because scientists are nothing if not imaginative).

1900: A third type was discovered, called gamma radiation. (Yes, I know, but what I do about it?)

1902: Pierre and Marie Curie show that beta radiation was nothing other than fast-moving electrons.

Still with me? Cool.

So anyways, Rutherford discovered this phenomenon before he knew that the particles were actually electrons, so he called them beta particles, and to this day the process whereby radioactive atoms break down and emit electrons is known as beta decay.

Okay. That was crazy-talk number one.

Now let’s continue with our timeline.

1904: Rutherford shows that alpha radiation is nothing other than helium nuclei. Now that may seem a little strange but it doesn’t qualify as a crazytalk. You see the bar is just too high.

**Crazytalk Number Two.**

Step right this way and mind your head on the way in; here we go.

Crazytalk number two says that (drumroll) **E = mc2**.

Now if this doesn’t seem crazy to you then it’s only because you have heard it so many times before. But take my word for it – it’s crazytalk all right. I should know: it is my word after all.

So it requires a little elaboration.

Remember we said that there are three types of radioactive decay; alpha, beta and gamma?

Well in alpha and gamma decay one atom breaks down into two or more smaller atoms (known as daughter products) but the total mass of all the daughter products afterwards doesn’t add up to the mass of the initial atom. We now know, thanks to uncle Albert and his famous equation, that the missing mass can be accounted for in the new-found kinetic energy of the daughter particles; that is to say these new atoms may weigh less than before but they sure move a hell of a lot faster.

Strange but true, so there you go.

If you got a problem with this don’t take it out on me – I’m just the messenger.

Okay. We’re up to date, we can go right back to the beginning and prepare ourselves for **crazy-talk number three**!

Even applying E = mc2 to this phenomenon of beta decay didn’t account for all the missing energy.

And as we mentioned at the beginning, the momentums didn’t add up either.

It got worse.

For a given type of radioactive decay, the mass *before* was constant so the energy of the electron which got spat out (remember the electron?) should have just one fixed amount of energy, even if that energy was less than what it should be.

But beta radiation chose not to act like this; it behaved like a sullen school-kid, containing as much energy as it wanted to have (up to a limit set by the E = mc2 formula), and for no other apparent reason other than just, well, because!

This became known as ‘*the continuous spectrum of the electron’* and caused no end of confusion and indeed desperation for the scientists involved.

The great Neils Bohr went so far as to propose that perhaps conservation of energy (which is one of the corner-stones of all science) didn’t actually hold at this level!

Fast forward to 1930: Up steps our man; the Austrian physicist Wolfgang Pauli. In December 1930 he writes the following letter [which I have obviously edited] where he predicts the existence of a new particle. Unfortunately he chooses to call this particle the neutron.

Pauli had a mate read out the letter to a science committee, because he wasn’t able to make the meeting in person.

4th of December 1930

*Dear Radioactive Ladies and Gentlemen,*

*As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save* [ *. . .*]  *the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...*

*Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December. With my best regards to you, and also to Mr Back.
Your humble servant.*

W. Pauli

It may not have been the ball which kept him away; Pauli was well aware of the ridicule he could have faced had he been there himself, as he later admitted to a friend:

*I have done something very bad today by proposing a particle that cannot be detected; it is something no theorist should ever do.*

What Pauli was referring to was the notion that all Science is built upon experiments; to predict something which can’t be subsequently verified by experiment is akin to discussing how many angels can fit on the head of a pin. You might as well discuss the existence of God. There’s nothing wrong with it; it’s just not science.

Luckily for Pauli he didn’t have to wait too long for further developments.

1932: The English physicist James Chadwick discovers the neutron, except he quickly realises that it is too heavy to be the particle imagined by Pauli. Chadwick therefore claims the name ‘neutron’ for his particle and there isn’t much Pauli can do about it. As far as most physicists are concerned Pauli’s particle might not even exist.

1933: Pauli is going to have another crack at it. Fortunately by now he has the assistance of another giant in the world of physics: the Italian physicist Enrico Fermi. Fermi decides to call the elusive particle a ‘neutrino’, which is Italian for ‘little neutral one’. Apparently.

Fermi was responsible for building the world’s first nuclear reactor in a University of Chicago squash court.

We’ll come back to Fermi and nuclear reactors in a separate program.

So this is Pauli take two; by now he is in a position to be a little more precise when listing the properties of his elusive particle:

*"... their mass cannot be very much more than the electron mass. In order to distinguish them from heavy neutrons, mister Fermi has proposed to name them "neutrinos". It is possible that the proper mass of neutrinos be zero... It seems to me plausible that neutrinos have a spin 1/2... We know nothing about the interaction of neutrinos with the other particles of matter and with photons.*

Well we now do know a little more about the interaction of neutrinos with the other particles of matter (thanks mainly to the work of Fermi). It turns out that there’s remarkably close to bugger-all interaction between the two. In fact is almost impossible to detect these reactions. But it’s not quite bugger-all. Collisions do occur, not very often mind, so to detect an interaction it helps to have a lot of atoms under observation. Something like a lake four stories high should do the trick, filled with nothing but baby oil, and surrounded by a bank of detectors which will hopefully pick up the tiny flash of light given off by the shudder of an atom as a neutrino passes by.

Then just wait.

And wait.

By now a new generation of scientists were in town, and the honour of discovering these elusive particles fell to two American physicists named Frederick Reines and Clyde Cowan who carried out this work in 1956 using a nuclear power-plant as the neutrino source.

But the story doesn’t finish there. No Sirree Bob.

What about the mass of a neutrino? Does it even have any?

By 1980 physicists had built enormous underground detectors in tanks containing some 400,000 litres of cleaning fluid to study solar neutrinos (neutrinos which come from the sun) in more detail. Why underground? Well because if it was above ground the liquid would get hit with other particles, particularly those called ‘cosmic rays’ or more specifically 'gamma rays’,

What are cosmic rays? That, I’m afraid, is for another day.

Well maybe I can just say a little.

Many of these gamma rays have been around since the time of the big bang, and because they are continually hitting our atmosphere and interfering with our communication equipment, it has estimated that when you view a television screen which has just static on it, approximately one percent of the image is due to these particles left over from the big bang. So as Bill Bryson puts it, don’t ever again complain that there’s nothing on tele; just sit back and watch the big bang for half an hour.

But I digress.

I guess that would be **Crazytalk Number Four**

The point is, by 1980 the scientists were used to detecting neutrinos, but now they had another problem; according to their calculations they should have been detecting three times as many neutrinos as they were actually detecting. It took them a while to realise what was happening. The other two thirds of these particles were changing into different types of neutrinos before they reached the detector (which was only built to detect the first type).

But then they realised something else also; the maths showed that only particles that have mass are allowed change type.

Conclusion: neutrinos have mass.

This was a big, and I mean BIG development.

First of all it tells us something about their speed; they must travel at less than the speed of light because no particle that has mass (called unfortunately ‘massive’ particles), can travel at the speed of light. This is one of the consequences of Einstein’s theory of special relativity.

Secondly, it has implications for another big, Big issue in cosmology (and we’re straight in to **Crazytalk Number Five**); it appears that most of our universe is missing. Somewhere between 90 and 99 per cent, in fact. It’s a little embarrassing to be honest. But one of a long series of mysteries to do with our weird and wacky world. You see we have a rough idea of the theoretical mass of the universe, based on the rate at which galaxies are racing away from each other. And we also have a rough idea of the amount of mass we can account for, based on the brightness of these galaxies. And the two just don’t tally. Not by a long way.

So it would appear that the matter we are looking for cannot be ‘seen’ in the conventional sense, hence the term ‘dark matter’.

But although neutrinos seem to be the only suspect in town, we need to be careful about putting them in the frame. Not least because if we get it wrong it’s going to make the headlines look ridiculous. “Free the solar 10 to power of a very large number” just doesn’t have quite the same ring to it is as “Free the Birmingham Six”.

And it is a very large number.

You want to know how large? Crazytalk Large! That’s how large!

**Crazytalk Number Six**

Over ten billion solar neutrinos pass through every square cm of your body every second.

Let me just repeat that for the hard of believing:

Over ten billion solar neutrinos pass through every square cm of your body every second.

And the fact that at night-time the Earth is between you and the Sun doesn’t matter – these little critters pass straight through the Earth!

So back to our missing mass; even if each neutrino is very, very, *very* light, the small mass it does have, multiplied by the sheer (literally?) weight of numbers, may make it the culprit.

Recent developments suggest that the neutrinos must have a mass smaller than a billionth of a hydrogen atom. Scientists therefore agree that the neutrinos make up less than 20% of the dark matter in the Universe, and that the rest has to be in some as yet unknown form.

One group has estimated that the ‘stuff’ of the universe consists of 5% ordinary matter, 25% exotic dark matter and about 70% dark energy.

You couldn’t make this stuff up.

While we’re in the general vicinity here’s another one to ponder:

We don’t know how the universe is going to end. Is it going to keep on expanding forever, with everything moving farther and farther away from each other, so that eventually all that’s left will be a dark and lonely void, referred to non-so-reassuringly as ‘The Big Freeze’?

Or will the universe start to contract again, giving us a ‘Big Crunch’ and if so will this result in yet another ‘Big Bang’ or maybe indeed this ‘Big Bounce’ is just a regular feature of what’s going on out there. Can it be the case that our universe is merely a basketball in the hand of some cosmological Michael Jordan, who’s just playing to the gallery as he sizes one up from downtown?

Is it indeed possible that I have, in fact, gone just that step too far in developing cosmological analogies?

I just don’t know anymore.

The bottom line is this: because we don’t know how much mass is in the universe, we just don’t know how it’s going to end. And that’s all there is to it.

By the way:

Fermi received a Nobel Prize in 1938 for demonstrating the existence of new radioactive elements, and for his related discovery of nuclear reactions brought about by slow neutrons.

Pauli got his in 1945 for the discovery of the exclusion principle which bears his name.

The Nobel Prize for the discovery of the neutrino wasn’t awarded until 1995, almost thirty years after Reines and Cowan detected them. By this time Cowan had passed on, and because Nobel prizes can’t be awarded posthumously only Reines was around to receive one.

If you want to stay in touch with neutrino developments, check out the Icecube Neutrino Observatory on YouTube. This is composed of a cube of ice of side one kilometre, or one billion tonnes which makes it the largest scientific instrument ever constructed.

Isn’t it cool that in order to see the smallest particles, we need the biggest instruments?

So, it would appear we’re pretty much done. Perhaps we should finish off by looking again at what you need to know about neutrinos for the state exam, followed by some short exam questions.

**Syllabus: Neutrinos**

* Radioactive decay resulting in two particles.
* If momentum is not conserved, a third particle (neutrino) must be present.

**Exam Questions**

**[2004] Momentum and energy do not appear to be conserved in beta decay. Explain how the existence of the neutrino, which was first named by Enrico Fermi, resolved this.**

Answer: Momentum and energy are conserved when the momentum and energy of the (associated) neutrino are taken into account.

**[2007] In beta decay it appeared that momentum was not conserved. How did Fermi’s theory of radioactive decay resolve this?**

Answer: Momentum is conserved when the momentum of the (associated) neutrino is taken into account.

Fermi postulated that a new particle called a neutrino had the *missing* momentum

**[2008] The existence of the neutrino was proposed in 1930 but it was not detected until 1956. Give two reasons why it is difficult to detect a neutrino.**

Answer: The neutrino is uncharged therefore it interacts very weakly with matter.

It also has a very small mass.

**Finally, because scientists don’t seem to have the imagination to help us appreciate the wonder that is the humble neutrino, let us turn instead to our colleagues in the humanities to help us out.**

**John Updike died in January 2009, but almost forty years ago he published a book of poetry which included one poem on the neutrino. The poem is called *Cosmic Gall*.**

**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 dustmaids down a draughty 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 inter at Nepal

And pierce the lover and his lass

From underneath the bed – you call

It wonderful; I call it crass.

*Telephone Poles and Other Poems*, John Updike, Knopf, 1960

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I hope you have enjoyed this podcast.

There is a link to the script for this talk in the *Particle Physics* page of thephysicsteacher.ie

Y’all come back now!

Adios.