## Astronomy Cast Episode 32:
# The Search for Neutrinos

**Fraser Cain:** I don't want to alarm the listeners but there is a flurry of particles from the Sun passing through each and every one of you right now. A lot of particles. In fact, there are 50 billion solar neutrinos passing through every one of us every second. Don't worry, you can't feel them; they barely interact with matter, but that's what makes them interesting.

All right. Let's talk about neutrinos!

**Dr. Pamela Gay:** Well, where do you want to start?

**Fraser:** Well… where did they even come up with the idea for them?

[laughter]

**Pamela:** Well back in 1930, Wolfgang Pauli was working to sort out nuclear reactions and we have a lot of different things that get conserved in particle physics and one of the things that we had to figure out how to deal with was how exactly do you go from a proton to a neutron? We know that it's possible for these two different atomic particles to transform one to the other, but the proton has charge and that charge has to go somewhere.

So, in trying to figure out what's happening he postulated this particle called the neutrino. We didn't know if it would have mass or anything, didn't really know anything about it, but it was originally created to conserve --- not so much to conserve, but to allow the change in quark type as you go from proton to neutron or between other different particles.

**Fraser:** Now, do you think we can sort that out?

[laughter]

I'm worried that people are going to go "quark type??"

[more laughter]

I understand that it's not easy to go from a proton to a neutron.

**Pamela:** Right

**Fraser:** And so, to get rid of that charge. So… I guess Pauli came up with an idea that one of the ways you could do so was if these theoretical particles called neutrinos were created at the same time.

**Pamela:** So there's a proton is made up of three different quarks: two up quarks and a down quark. A neutron is also made of three quarks but in its case it has one up, two down. So somehow in the process of changing from a proton to a neutron we need to figure out how to convert a quark from an up quark to a down quark.

**Fraser:** Right, and quarks are some of the fundamental particles that make up protons and neutrons, right?

**Pamela:** Yes. There are certain fundamental atomic particles – an electron, for instance, is a fundamental particle. You can't make an electron into smaller bits. Protons, you can break into three bits called quarks. What was proposed was this thing called a neutrino would be part of the reaction and when the neutrino comes out, it allows this change to take place and allows all the things that need to get conserved in the reaction to get conserved.

Depending on what website you look at, some people listed as being Fermi in 1930 and some people listed as being Pauli in 1930 – one of these two brilliant men in 1930 came up with the idea of the neutrino to allow this change in quark flavour during nuclear reactions.

**Fraser:** All right, and so back in the day what did they think they would be looking at.

**Pamela:** Um. They didn't know.

So you come up with an idea of… "there's something we're missing in our theories" but you can name it but you can't necessarily just pre-define its characteristics. So they named this thing sort of like we have this mystery particle called a Higgs-Boson for mediating gravity. Do we know anything about it? Not really. We have hints. They also had hints about what the neutrino would have to do. It would have to react via the weak nuclear force and probably via just about nothing else because otherwise we probably would have seen it by then.

So they postulated this particle, said it reacted via the force that allows protons and neutrons to have their identity, and then we spent a lot of years looking for it. It was finally experimentally observed in 1953.

**Fraser:** So what was the first experiment – or what were some of the failed attempts? What were they trying to do?

**Pamela:** So one way to look at it is you look for something that has changed its structure, changed its identity. What they were looking for was changes – in this case it was cadmium that changed. They were looking to see what sort of nuclear reactions they could cause and then looked at what was left in the atoms that changed. What did you start with and what did you end up with? Those changes get attributed to the neutrinos and the reactions that the neutrinos have.

**Fraser:** And so, what kind of an experimental apparatus did they have?

**Pamela:** So, in the first reaction they had a section of cadmium and it started out as cadmium 108 and a neutron. When the neutron came in it became cadmium 109 and a gamma-ray and this gamma-ray was detectable. There were predictions about what energy we should have, what we should see, how the cadmium should change, and what we saw was exactly what was expected in terms of the changes in the amount of light that was given off.

The catch is, you look for the light that is given off during the reaction as the neutrino is interacting with other particles.

**Fraser:** So they had a nuclear reactor streaming off neutrinos and I guess in this process protons were being turned into neutrons and neutrinos were streaming off. The stream of neutrinos was slamming into this cadmium chunk and they had detectors around it and they were watching for gamma-rays. When they got a gamma-ray come off, then that matched their predictions and they knew they'd seen an interaction of one of these neutrinos with the cadmium.

**Pamela:** Exactly. One of the neat things about these is any nuclear reactor will be giving off bazillions of neutrinos. In fact, with the early nuclear reactor that they were using when they did this experiment they were expecting neutrino fluxes of 10^12 to 10^13 neutrinos per second per square centimetre. That's a really tiny space and an awfully high flux of neutrinos.

The thing is, these things really, really don't like to interact. You have to have these huge fluxes in order to detect just one or two or three reactions when you're lucky.

**Fraser:** When you say flux, you mean a lot of particles?

**Pamela:** Whenever you say that there's 10^12 to 10613 neutrinos per second per centimetre squared you're saying how many neutrinos are going out through an area in a unit of time. You can also refer to the water coming out of your hose as a flux of water. You can say how many gallons of water is coming out through the, perhaps square centimetre opening of your hose.

**Fraser:** I think of how you have those caves with bats coming out all at the same time, zipping past…

[laughter]

**Pamela:** That's another way of flux, yeah.

**Fraser:** Okay, so they've made their detection of what a neutrino is, how does the science progress from there?

**Pamela:** We have theories for how the Sun should be working. We had predictions on how many neutrinos the Sun should be producing and in fact we think that the Sun produces over 200 trillion, trillion, trillion every second. So, with that sort of prediction, we then figure out , "Okay, those neutrinos are getting spread out in all directions in a sphere, then we figure out how big the planet Earth is, how big our detector is, and how many neutrinos should be passing through any particular detector at any particular moment.

Then you figure out, "what's the likelihood that a neutrino is going to interact with something in my detector?" Work through all the probabilities… work through all the probabilities and then you make a prediction on how many neutrino detection events you expect in a given month or given year. They did all sorts of experiments looking for these different hopeful detections and they only found one third of what they actually expected.

The original experiment of solar neutrinos was done by Ray Davies. He had 600 tonnes of chlorine in a tank in a mine in South Dakota. He detected one third of what was expected and everyone scratched their heads. We started asking questions: do we not understand what's going on with the Sun? Do we not understand neutrinos? Are, perhaps, neutrinos preferentially going off in a particular direction that is not toward us? There were lots of different questions. Was something happening to the neutrinos on their way to the Earth?

Many different experiments were done to try and see if we could repeat what he did, and consistently we were finding one third of what we should be finding. This became the solar neutrino problem for the Sun and it was a major problem up until fairly recently when we discovered physics sometimes does some really strange things.

**Fraser:** According to their calculations, they had calculated how many of these neutrinos should be streaming off the Sun, but there was only a third? Not off by 10%, or seeing 95% of what they were expecting… but one third

**Pamela:** Off by a third.

**Fraser:** Right, they were getting one third the number. So what's the answer? I want to know.

[laughter]

**Pamela:** Well, the answer we believe is, the neutrinos are able to change flavours. Just like quarks have flavours (up, down, strange, charm), neutrinos also have flavours. There are electron neutrinos that are associated with reactions involving electrons. There are muon neutrinos, there are tau neutrinos, and each of these different types of neutrinos is created in a different type of nuclear event involving different combinations of quarks.

It's possible for mass and energy to flip flop one from the other. It doesn't generally happen – you aren't going to spontaneously turn into a puddle of energy while you and I are talking – but with a neutrino it's possible for these extremely low-mass bits of matter to spontaneously decide, "I need a little bit more energy, I'm going to have a lower weight right now" and they can oscillate between different kinds of energy and mass. It just works out that since there's three flavours of them between us and the Sun the electron neutrinos produced in the Sun can split three ways into electron, muon and tau neutrinos.

**Fraser:** So these different kinds of neutrinos don't interact with matter in the way that the electron ones do.

**Pamela:** Exactly. We need different types of detectors to detect all three different types of neutrinos. Now, current way of trying to look for these things is there's a new neutrino detector, the Sudbury Neutrino Observatory up in your part of the woods – well, at least in Ontario which is in your country. They're able to detect all three different types using heavy water.

**Fraser:** Okay, what's the apparatus like in Sudbury?

**Pamela:** So they have a giant tank of heavy water that is floated in a container of normal water. Heavy water is made out of a deuterium atom instead of a hydrogen atom, where deuterium is a special form of hydrogen that in its core has a proton and neutron instead of just a proton. This isotope of hydrogen reacts slightly differently. If you have an electron neutrino come in and hit one of these heavy hydrogen atoms, the heavy hydrogen atom can split into two protons and an electron. This is one of the reactions that we can see.

**Fraser:** So once again… they've got the heavy water inside, floating on regular water, and then a ring of detectors all the way around it so if any one of those different kinds of neutrinos interacts with a particle, they'll see a flash of – is it a gamma-ray again?

**Pamela:** It's not just a ring of detectors, they actually have to surround these tanks with an entire sphere of detectors that look for the light that can be shooting off in all sorts of different directions.

So you have this tank that is surrounded by thousands of different photo multipliers which look for very, very faint flashes of light. We call this Chrenkov radiation. It's actually a shade of blue, according to the Sudbury website. So they're looking for light blue light, a slight flickering of this Chrenkov radiation as the neutrino passes through the heavy water and just happens to hit a deuterium atom and then cause it to flip into either two protons or, depending on what they're observing, they observe different slight variations.

They can sometimes end up with a neutrino coming back out of the reaction and the deuterium splits into a proton and a neutron. Sometimes they also end up with scattering reactions where the neutrino will come in and scatter off of an electron. So you have all these different types of different reactions taking place and its because of all these different possible detections that they're able to detect all three species of neutrino with their one detector.

**Fraser:** Now how is it possible that these particles can bore through so much material and not interact and collide? How can there be 50 billion particles passing through me?

**Pamela:** well, you have to consider the cross-section of the collision. What this means is, say you and I are walking across the room. The cross section of our collision is the size of your body and the size of my body and if as we approach one another our two cross-sections overlap, we're going to knock each other. Some particles have larger cross-sections because of the forces that end up taking place during the crossing.

If you send two electrons toward one another, the electromagnetic force will try and repel them, so they don't even have to touch each other to affect one another. This force radiates through space and will cause the two electrons to bend their paths to keep them from colliding.

**Fraser:** Right, it's like trying to push two magnets of the same pole together.

**Pamela:** Exact same force.

**Fraser:** They don't even have to touch for them to bang.

**Pamela:** Exactly.

Well, the neutrinos, they only react via the weak force which has a very, very small cross-section. So without the electromagnetic force, without the strong force, without anything else being present to cause the particles to collide without actually touching one another, the neutrinos can pretty much pass through the empty space of an atom.

You and I are mostly empty space. It doesn't feel that way when you stand on the bathroom scale, but the reality is that our atoms have more nothing in them than something in them. What holds all of these bits apart is the electromagnetic force.

**Fraser:** Just how little do they interact? How much stuff would they have to go through before they finally collided?

**Pamela:** You could fill the entire space between us and the Sun with this heavy water and if you send just one neutrino through, it might just keep going. You need vast, vast quantities of material before you finally guarantee that an actual collision is going to take place.

**Fraser:** What about something denser like lead, or gold?

**Pamela:** You'd need to have about 22 light years of lead before you finally guaranteed that there'd be a collision.

**Fraser:** 22 light years of lead??

**Pamela:** Yes.

**Fraser:** To guarantee that you'd stop a neutrino??

**Pamela:** Yes.

**Fraser:** That's – I guess they really can pass through something. Okay.

**Pamela:** The mean free path of the neutrino, for those of you interested in the scientific vocabulary, is 22 light years of lead. One of the neat things is they actually don't see the planet Earth when they're looking for neutrinos. So when you have your detector pointed at the Sun at noon, you see neutrinos. When you have detector pointed away from the Sun at midnight you see the neutrinos. So it's fair to say that you're illuminated from the head down with neutrinos at noon and from the feet up at midnight.

**Fraser:** It'd be like pointing your telescope to the ground in the middle of the day so you could see the stars on the other side of the Earth.

**Pamela:** and they actually bury these detectors. The Sudbury Neutrino Observatory is two kilometres down. The reason they do this is to make sure there's nothing else affecting the event. They have this set-up, this giant heavy water tank buried two kilometres under the ground and this way any stray high energy protons, any other stray high energy particles coming from the atmosphere are pretty much guaranteed to interact with the rock and other material that's between the surface of the Earth and where they actually put the detector.

**Fraser:** Let's put this in context for astronomy. How does this play a part in some of the research going on in astronomy?

**Pamela:** It allows us to understand if we know for certain if the nuclear relations are doing what we think they're doing. It has some neat implications.

Back in 1987 there was this fabulous supernova in the Large Magellenic Clouds, 1987a. Our good friend Phil Plait was one of the researchers who studied it. About the exact same time they were first detecting light from the supernova, they were detecting neutrinos from the supernova.

So we were able to say with certainty, "yes, we know there are nuclear reactions going on within the supernova that are changing atoms from one type to another as the elements build larger." We see the neutrinos from that exploding star off in one of the nearest nearby galaxies.

**Fraser:** So would neutrino telescopes be another way to look at objects in space? Could you detect supernovas before – maybe stuff that's obscured through dust and gas?

**Pamela:** It's a way to know that there are some sorts of nuclear reactions going on out there. If we got this huge, sudden flux of neutrinos we could say, "well, there's an obscured supernova, or a nuclear blast somewhere, or there was some sort of dark explosion" (but I can't think of anything that would be dark enough that we wouldn't get any light from it). A supernova on the other side of the galaxy… there's a lot of dust and gas between us and there and we probably need to start looking in the infrared for that supernova and we don't naturally go looking for supernovas in that direction.

**Fraser:** So, could we see neutrinos from the Big Bang? As I recall when we talked about the Big Bang, it is a gigantic nuclear reaction – was, for a brief period of time. So would there be neutrinos generated from that?

**Pamela:** Yes, and in fact they're still hanging around. There's a background of about 1000 neutrinos per cubic centimetre that have a background temperatures of about 2 degrees Kelvin. What's neat is the neutrinos separated from the light and mass a little bit earlier than the light and the mass separated from one another. So for a while, all the neutrinos, all the photons, all of the atomic nuclei in the Universe were thermally coupled to one another, they were constantly reacting and interacting.

As the Universe cooled, it first reached a temperature where the neutrinos stopped interacting, they stopped having a very short mean free path and they were allowed to fly free across the Universe. It was only after that point that the light and the matter finally started to separate from one another and the Cosmic Microwave Background was established.

**Fraser:** So we actually have something that happened before the Cosmic Microwaves Background Radiation?

**Pamela:** Exactly, and its really a pity that we don't really have a way to take a look at that neutrino background that's also mapping out the earliest moments of our Universe across our skies, but neutrinos just don't like to interact and we don't have the high resolution, high sensitivity equipment to get any sort of a spatial resolution on this cosmic microwave background – or, not microwave, cosmic neutrino background particles.

**Fraser:** So what does the future hold for this? What are some up-coming experiments or research that's being done?

**Pamela:** Well, Mini-boon, which is an experiment that uses an accelerator to create the neutrino stream, is looking to figure out "so, we have these neutrinos, how quickly do they oscillate? Can we replicate the oscillation experiments?" So we're trying to figure out over what distance do  these things oscillate between flavours can we confirm the oscillations between flavours? Once we've confirmed it, can we say, "if you're on

Mercury you're not going to see this 1/3rd lowered, perhaps you'll see it only 2/3rds lowered. We're trying to figure out how the oscillations take place, over what distance scales, time scales these oscillations take place. We're always looking for new ways to try and detect them with greater sensitivity so that perhaps we can better understand all the different things, all the different nuclear reactions that are producing neutrinos in the Universe.

**Fraser:** All right, I think that gives a good overview of neutrinos. I still find that amazing, that they can go through 22 light years of lead.

**Pamela:** Yeah. Now, it's not to say they're guaranteed to, but on average that's how much you need to guarantee that somewhere in that, there'll be an interaction. These things refuse to interact with anything.

**Fraser:** One last question: is it possible that these are dark matter? That this is an explanation for dark matter?

**Pamela:** That's actually one of the things that caused the hardest hunt to see if there were these oscillations in flavour. To have the oscillations you have to have the mass. With a thousand of these things per cubic centimetre, you can get a whole lot of mass out of these particles. When we discovered that yes, they are oscillating, that meant that they had to have mass that the energy and mass were interchanging between. So some fraction of the dark matter in the Universe is neutrinos.

Now, people have tried to calculate the upper limits on just how much mass these things can have, and still find that it comes nowhere near accounting for the type of dark matter that we're thinking we have to have based on rotation curves and measuring how much gravity is in galaxy clusters. But it's a start. It now tells us that there is this class of particles out there that are limited in how they interact, that can still have mass.

**Fraser:** We'll just have to keep looking. Thanks Pamela!

*This transcript is not an exact match to the audio file. It has been edited for clarity.*