Astronomy Cast Episode 105:

The Strong and Weak Nuclear Forces

Fraser Cain: When you were in the middle of doing your live show at Dragon Con, I was moving. We're all moved in, lots of boxes all over but I've got Internet so that's all that really matters.

Dr. Pamela Gay: Does anything else really matter?

Fraser: No, just the Internet. Thank you for doing the Dragon Con Live recording. That was really cool to have Phil and Dr. Grazier.

Pamela: Next year we really will have you there even if I have to kidnap you.

Fraser: That's fine, sure. I'll come. Let's move on then. We have a big surprise coming which if we can get ourselves organized and then it will just show up in the feed. That's all I'm going to say on that.

After a quick Dragon Con break, we're back to our tour through the fundamental forces of the Universe. We've covered Gravity and Electromagnetism. Now we're moving on to the strong and weak nuclear forces. We didn't think they would need separate episodes so we're going to put them together.

Then we'll cap the whole series off with our quest for the search for the theory of everything and that's when we win our Nobel Prize. [Laughter] I can't wait. I hear Sweden is very nice this time of year so I'm really looking forward to that. So where do you want to start, strong or weak?

Pamela: Let's start with strength. Let's start with the Strong Force.

Fraser: Okay, now what is the Strong Nuclear Force?

Pamela: It's essentially what holds the nuclei of Atoms together. If you've looked at a Periodic Table recently you'll notice that it starts to get a little fuzzy around Element 100 or so. As you start to get these really big nuclei, the Strong Force isn't quite strong enough to hold everything together. For smaller Atoms, it does a very good job it is in fact one of the strongest forces we have out there which is why it is called the Strong Force.

What it essentially does is to cause little particles; Gluons in this case, fly back and forth. As they fly back and forth, they glue the different particles together. This is an extremely useful thing because otherwise Protons and Neutrons really don't have any reason to stick together with the Electrostatic Force. One is charged the other is neutral. You have to have some other force to hold these pieces together.

Fraser: Right, so at the center of the Atom, you have your Protons and your Neutrons and they are being bound up together by the Strong Force. But not Electrons, right?

Pamela: No, the Electrons come in using strictly Electrostatic Force.

Fraser: Okay. I know you can break up Protons and Neutrons into more elementary particles. Is the Strong Force holding those elementary particles together as well?

Pamela: This is where we start to get into a sub-part of the Strong Force sometimes referred to as the Color Force. Protons and Neutrons are made up of different flavors of Quarks. You have up and down are the two stable Quarks that go into making pretty much everything around us stick up. So your Protons and Neutrons are both made up of combinations of up and down.

The Color Force is part of what gets in as its own form of the Pauli Exclusion Principle. You have this idea with Electrons that you can only have a spin up and a spin down orbital. If any of you have taken Chemistry, this is what explains the entire crazy orbitals of Atoms thing that you had to memorize in tenth or eleventh grade.

With Quarks you have the same thing going on where you can't have three Quarks that are the same color all in one Proton. Instead you have to have combinations of colors. Just for the sake of having names they're generally referred to as primary colors but they're not a real color. There's no real color involved, we just needed a word.

So instead of making up a word, we decided to abuse a word. With the Strong Force we have the Protons and Neutrons are all made up of Quarks and the Quarks are held together with the Color Force which is part of the Strong Force.

Fraser: Now you said that there are Gluons zipping back and forth between the particles and that's what is communicating the Force, right?

Pamela: And this is actually also what limits the Force to such a short distance. Gluons have mass and because Gluons have mass the Heisenberg Uncertainty Principle which says you can either know where something is or how fast something is moving and it gets involved in other things.

It says that once you end up with something as heavy as a Gluon you're limited in how far you can go, how far you can interact to about ten to the fifteenth of a meter. So, that's a zero followed by fourteen more zeros and a one. Zero point 14 zeros 1 meter is the distance at which a Gluon is capable of holding things together.

Fraser: And Gluons have actually been isolated in Particle Accelerators, right?

Pamela: They were first detected back in 1979 and since then we have been turning them up in various different places. Stanford Linear Accelerators played with them; Brickhaven National Laboratories has played with them. All sorts of different Colliders and Accelerators have played with them. We know they're there. We can quantify different characteristics about them. This part of Physics we're quite certain about.

Fraser: So if you then were able to intercept Gluons that were communicating back and forth between a Proton and a Neutron they would fall apart if you were able to sort of siphon away the Gluons?

Pamela: Well that's kind of the wrong way to think about it. All these things that are communicating for us can also exist independently. For instance with the Electromagnetic Force that we covered a couple weeks ago, you have Photons moving back and forth.

In some cases we refer to them as Virtual Photons because you don't really see them. It is these Photons that are communicating with the Electric Fields and the Magnetic Fields.

Photons can get shot out of a laser beam and they are quite happy to exist as stand-alone particles. If you create enough energy in some sort of collision then out of that energy you can start to get particles just materializing. So, in this case we have something with a mass that is a little bit less than a few mega-electron volts.

We just need to collide something so that you end up with more energy than that with the correct decay rates where you end up with Gluons as part of this energy condensing down the stable particles. They can exist without having to be trapped inside of a Nucleus.

Fraser: Right. So what is the strength of this Force compared to say Gravity?

Pamela: In general the way we talk about Forces, it's easier to not say, "this has this many Newtons of Force." But we instead look at the relative strengths of Forces. So, let's say, because it's true, that the Strong Force is the strongest of all the forces. Well, then the Electromagnetic Force between two particles that are nearby compared to the Strong Force it has a strength of one one hundred and thirty-seventh of that.

So if you stick two Protons next to each other in the Nucleus of an Atom, the Strong Force holds them together with a Force we're going to call one. But at the same time because they're both Protons they're trying to repel each other. Likes repel likes in this case.

The Force that is trying to push them apart is one divided by one hundred thirty-seven times smaller than that Strong Force. Now, at the same time, if Gravity is trying to hold those two Protons together, here we get into ridiculously small numbers.

Those two Protons trying to push each other together compared to the strength of the Strong Force holding them together is six times ten to the negative thirty-ninth. So, you take a zero and you take a one, you put thirty-eight zeros and then a six and that is how much weaker this Force is.

Fraser: Right, and so the equivalent to think of an analogy is like you have magnets with two pointing towards North, you take the two North sides of your magnet and just jam them together. [Laughter] You can hold the magnet together with the force of your arms.

You can overcome the Magnetic Force there and then as soon as you let go of the magnet they pop away from each other. Even though Gravity is pulling the Protons together, the Electrostatic Force is pushing them apart. The Strong Force is dominating it and it's the thing that's really holding them together.

Pamela: Here there reason that we're able to see Protons repelling each other at other distances is as soon as you get past that ten to the negative fifteenth of a meter the Protons no longer care about the Strong Force. So in order to build the Nuclei of Atoms you have to get within this very limited distance.

You have to slam the Protons together the same way you might slam two magnets that are trying to repel each other apart together. Once you get them close enough, the Strong Force overcomes.

Fraser: We've covered the Strong Force, so why don't we switch over and learn about the Weak Force, what is it?

Pamela: The Weak Force is how we look at Atoms and we observe them decay and we had to explain this somehow. What is it that is causing all of a sudden one Atom decides it is going to transform itself into something that has the same number of stuff in the center, the same number of Protons plus Neutrons in the center?

But all of a sudden, one of the Protons decides it is going to become a Neutron and thus the Atom changes names while maintaining very close to the same weight. This is beta decay.

Fraser: Give us an example of something that might decay.

Pamela: For instance if you have a Plutonium 15, this is one of the things that crops up in all sorts of different radioactive experiments. That will end up decaying to Strontium 16.

So, you've changed the number of Protons, increased the number of Protons, decreased the number of Neutrons and along the way you've given off an Electron and you've given off an Electron Neutrino. This helps keep everything balanced out.

Fraser: Right. The amount of energy in the whole system stays the same.

Pamela: Charge is conserved so you went from the Neutron to having a Proton and an Electron and then there's an Electron Neutrino to help things out.

Fraser: So the math works; like you could sit down and add up all the particles before in the energy and add up all the particles after in the energy and it all balances back out again.

Pamela: Just to get the details correct, it is an Electron and an anti-Electron Neutrino. Those two come in pairs together.

Fraser: Right, but I guess the question then is why? Why does this just spontaneously go 'pop'? [Laughter] And then you have a completely different element.

Pamela: It's the constant quest to find the lowest possible energy level. Neutrons in general aren't the most stable of things. If you leave a Neutron alone on a shelf for fifteen minutes it will decide it wants to be a Proton, and Electron and an anti-Electron Neutrino.

It's kinda hard to leave a Neutron alone on a shelf but if you could, and they do this in various types of experiments, in Atoms usually states that have lower energy are better balanced. It gets a better distribution of particles in the center such that it is at a lower energy level.

In the quest to achieve the lower energy level, you end up with Protons changing over to Neutrons or sometimes the reverse. It depends on the particular reaction. It just happens to be that it is the Weak Force that makes this happen. What's actually happening is that you have Quarks changing from up to down.

So, as you go from that Plutonium to that Strontium, what is happening is one of the down Quarks transforms into and up Quark. That gives us the Neutron going into a Proton and it's that change from down to up that is triggered by the Electro Weak Force.

Fraser: Then how was the Weak Force discovered?

Pamela: There is first of all just the fact that WOW we have things decaying. We have different particles where we see Electrons coming off; we see the nature of the Atoms changing. Radioactive decay happens and so we had to explain what was going on.

As we built the standard model of Particle Physics where we saw that Protons and Neutrons are made up of Quarks we realized that somehow a Proton had to change into a Neutron or vice versa depending on the particular reaction.

This meant that somehow we had to conserve all these different qualities and we needed something to mediate all of this and that's where we started looking for the Weak Force. It actually wasn't until the 1980s that we finally started to be able to find the particles that mediate all of this. That's the amazing thing about this, for most of our listeners. This is stuff that has happened in all of our lifetimes.

In the case of the Weak Force, it is moderated by what we call Vector Bosons. In this case they have masses of greater than eighty giga-Electron volts which is a lot, not that people tend to think in giga-Electron volts. This large mass, this mass that is a lot bigger than the mass of the Gluons that mediate the Strong Force means that this particular Force only acts over distances smaller than a Proton. It can only affect things at the particle size.

What are mediating this are the W and Z Bosons. So we again have Bosons and these Bosons were detected in the 1980s, again by creating really high energy experiments where the energy fell out into a variety of different particles that in the cascade of energy and the stable particles along the way the Vector Bosons became apparent.

Fraser: That seems quite amazing to me that you could perform the big collision, freeze out the energy into the particles and then have a particle bounce against one of your detectors and then say: "Hey you know, that's probably the particle that communicates the Weak Force." [Laughter]

I'm trying to think how they would do that. Did the Scientists then in their calculations from one of their theories say, "if a particle of this amount of energy and mass bonks against your detector that's what it has to be"?

Pamela: It's actually even more subtle than that. What you do is you collide things violently inside of a detector. Often you'll end up with essentially donut shaped accelerator rings. You have two rings running parallel to each other except the particles in one are going clockwise and the particles in the other are going counterclockwise.

Then you feed them together inside of your Detector such that you're forcing two different streams of particles to collide inside your Detector. Then as this amazing release of energy where you have the energy that is in the mass and the energy that is in the velocity of these particles all coming together. This energy then freezes back out into a cascade of particles that in many Detectors are now moving through magnetic fields that have been put in place.

How the particles move through the magnetic fields is a function of what is their mass, what is their velocity and what is their charge. By looking at what are often really neat curly Qs, what are really neat bent paths through these magnetic or electric fields, we're able to backtrack through well, this seems to have had this reaction time. We can figure out the velocity it lasted this long. It curved this much in that amount of time which means it probably had this amount of charge.

We look at all of these different characteristics and look at how they moved through the Detectors in a variety of different ways. Sometimes fiber optics is being used; sometimes you're doing this in gases. There are all different ways that you can detect these different particles.

It's by looking at their paths at different points that we're able to work out what the masses had to have been, what the charges had to have been and figure out what it is exactly that we're looking at. Sometimes we're not entirely sure. There's been some, "well it could have been", observations of something that might have been the Higgs Boson but no one believes the results.

We know that there's something there but we're not positive what it is because the results weren't solid enough. There weren't enough particles produced, there wasn't enough signal in the Detector…It's a frustrating game.

It took until I was an undergrad at Michigan State for the final of the Quarks to be found just because it was such a massive particle that trying to get enough energy to generate it is a cascade effect. You can't just say "I need this many giga electron volts", and it will create a top Quark. You have to overshoot and see what falls out of the energy that condenses down.

Fraser: Well we're only about a week away from them firing up the Large Hadron Collider and the search for the particles begin and not the destruction of the Earth.

Pamela: No, Earth is not going to be destroyed.

Fraser: It's a search for particles. I guess the question is, how are they connected? They're both called Nuclear Forests.

Pamela: At extremely high energies, things start to all unify. We're still trying to understand all of this. There are so many things about Particle Physics that we're still working to try and understand.

With the Standard Model of Particle Physics as you move toward higher and higher energies, there seems to be a point and a density at which things are crammed together to the point that you achieve the energies that go through the Strong Force and the Weak Force combined and act in one way.

But at this point you also sort of have the soup so talking about individual Atoms starts to get trickier. This is how we're slowly trying to move towards a grand unified theory. This is something that we're going to talk about more next week as we start to talk about how we're going to get our Nobel Prize, which really we won't. We're just going to sorta repeat what other people have said.

Fraser: Hey, that's quitter talk! [Laughter] We are so going to get a Nobel Prize.

Pamela: Right now what we talk about is the Electroweak Unification and there actually has already been a Nobel Prize for this. We discovered the WZ 22:33particles, the Intermediate Vector Bosons that convey these Forces back in 1983.

There is a Nobel Prize given to Weinberg, Salam and Glashow – I have probably mispronounced their names terribly. Weinberg is the only one I've met, so the other two haven't told me yet how they say their names.

It's thought that at high temperatures where the energy of all these particles colliding one against the other against the other is about 100 giga electron volts. At these extremely high energies, the weak and electromagnetic interactions all start to be a manifestation of a single Force.

We're still working to try and put these things together. Our basic picture is at energies where Quarks start to be their own separate happy little particles we have four Forces acting completely separate from one another.

But, as you start to get to energies of about one hundred giga electron volts, which we actually had when the Universe had a temperature of – and pardon the scientific notation – about ten to the fifteenth Kelvin. You don't say degrees because Kelvin is its own special thing. At one followed by fifteen zeros Kelvin the Universe was so hot and so dense that the Electromagnetic and the Electroweak Forces combined into one Electroweak Force. This occurred when the Universe was a little bit younger than ten to the negative tenth of a second.

Fraser: So, early on.

Pamela: Yeah. [Laughter] Well before the first second it was done transpiring. By second one yeah, everything was nice and happy and we had Quarks were separate and all the Forces were separate.

But early on at that little less than ten to the negative tenth of a second, we only had three forces: the Electroweak, the Strong and the Gravity. Now if you keep going a little bit further back in time and get to so it's about ten to the 27 Kelvin, at that point we start to be able to bring the Electroweak and the Strong Force together as well.

Where we get lost is when we try and bring in Gravity. The details of how you unify the Electroweak and the Strong Force we're really not so sure on, but we're pretty sure it happens. We're working to try and build a model that explains magnetism, explains electricity, explains Beta decay, and explains how it is that the Nucleus itself holds itself together and why it is that we don't end up with Atoms the size of the Solar System. Why is it that we have a finite size to the nucleus of an Atom? The finite size of the Nucleus of an Atom comes from the Strong Force having a limited distance.

The Beta decay comes from the Weak Force. Electromagnetism is what brings the Electrons and the Protons together and allows molecules to form and allows refrigerator magnets to adhere themselves to refrigerators. One of the neat side effects of trying to unify these three Forces, the Electromagnetic, Weak and Strong Forces is pretty much all of the theories out there predict that Protons decay. There is no observational evidence for this.

In fact, all observational evidence points towards Protons really not wanting to decay. If they do, they do it over extremely long lifetimes. But if Protons do decay and our current ideas on how you might unify these three Forces are true, then trillions of years from now when all the Stars are dead, when all the Black Holes are sitting there happily evaporating away. When maybe there are one or two dead cold White Dwarfs floating around but maybe not. Everything that is left, any Protons that are out there are going to start to decay.

That means that even any Rogue White Dwarf Stars that just might happen to have survived are going to evaporate. Any Rogue Planets that might have survived are also going to decay away as the Protons simply become energy.

That's even a more depressing future than some of the ones we've looked at before, but we don't know if this is true.

Fraser: I think it's equally as depressing. [Laughter]

Pamela: You think so.

Fraser: I think they're really just exactly the same, yes. [Laughter] Okay, well and you're already starting to ruin next week's shows. I have to stop you.

Next week we will talk about the quest and the discoveries that were made and that were to bring everything together. We'll probably have another look at String Theory just because that's part of it.

This transcript is not an exact match to the audio file. It has been edited for clarity.
Transcription and editing by Cindy Leonard.