Physics for the 21st Century

Unit 1: The Basic Building Blocks of Matter

Bonnie Fleming and Mark Kruse

What are the basic building blocks that make up all matter?

> BONNIE FLEMING: *The basic building blocks of matter are the bits of particles that we cannot seem to break apart into any smaller particles.*

The Standard Model of particle physics is the best theory that physicists have to describe these elementary particles and the forces that influence them.

It is one of the greatest scientific achievements in recent history. But the theory is incomplete.

Bonnie Fleming, of Yale University, is working at Fermilab where they are developing new detectors to investigate one of the least understood particles of the Standard Model: the neutrino.

Through their research, the team believes they may uncover physics outside the Standard Model.

> BF: *The Standard Model is a beautiful description of our particle world. And, finding something that doesn't quite fit in the Standard Model is therefore always a surprise.*

Mark Kruse, of Duke University, is searching for a particle predicted by the Standard Model that has yet to be observed: the Higgs boson. At Fermilab, Kruse uses the "Tevatron," the largest particle accelerator in the United States, to try and discover this elusive particle.

> MARK KRUSE: *Everything's been observed in the Standard Model except the Higgs boson. So, it's a huge question right now that would really fill the Standard Model.*

Both researchers are looking to fill the gaps in the Standard Model in hopes of gaining a better understanding of the fundamental particles that lay the foundation for all matter.

Part I: Neutrinos

Bonnie Fleming

At Fermilab, outside Chicago, Illinois, scientists are researching the most fundamental particles of nature.

> BONNIE FLEMING: *This is the premiere high-energy physics laboratory in the U.S. It's the cutting edge of high-energy particle physics. A hundred years ago, scientists looked at the particles and particle physics that had been discovered and thought they were done. The proton and the neutron and the electron seemed to be the fundamental particles that made up everything else we see in the Universe. But now, when we try to break the world down to the smallest building blocks of matter, we come up with the twelve elementary particles of the Standard Model.*

Deep underground at Fermilab, Bonnie Fleming is part of a research team examining one of the least understood of these particles: the neutrino.

> BF: *The neutrino is even within the Standard Model, rather unique, very small -- that's the "ino" part of neutrino -- and neutral, electrically neutral. And, there are three different flavors. There is the electron neutrino, which is paired with the electron, the muon neutrino which is paired with the muon, and the tau neutrino which is paired with the tau.*

Neutrinos, originally thought to be massless particles produced in radioactive decay, were first detected directly in the laboratory in 1956. Physicists moved on to study neutrinos produced in the sun and upper atmosphere and were baffled when they didn't find anything close to the number of neutrinos predicted. The solution appeared in 1998, when the Super-Kamiokande collaboration announced that neutrinos oscillate.

> BF: *We've discovered that neutrinos oscillate all the time. And, it was a big surprise to people. And, because neutrinos oscillate, we know they have mass.*

Neutrino oscillation is when a neutrino changes from one variety of neutrino into another. The neutrino can change back and forth, oscillating as it travels through space. This explains the apparent lack of solar neutrinos. Neutrinos originally produced in the sun had oscillated by the time they reached earth. Neutrino oscillation also implies that neutrinos have mass.

> BF*: It took us a long time to convince ourselves that neutrinos have mass. One of the things that sets neutrinos apart from the other*

building blocks of matter is that their mass is at least extremely small, orders of magnitude smaller than any of the other fundamental particles. So, you can't measure their mass in the way that we measure the mass of the other fundamental particles. So, we had to look for another phenomena that would be a suggestion that neutrinos have mass.

According to quantum mechanics, in order for neutrino oscillation to occur, the neutrinos must have slightly different masses. If they were massless or had the same mass, they wouldn't oscillate.

BF: *You can think of neutrino mass states as different pitches on a tuning fork, okay? And if the two pitches are the same, meaning the masses are zero or exactly the same, and you strike them, you'll hear the same pitch but just louder, an increase in the amplitude. If, by contrast, the two tuning forks have slightly different pitches, when you strike them, you hear a beading effect. And that beading effect is just like an oscillation. The fact that you have two neutrinos with different masses or two tuning forks with slightly different pitches, when they mix with each other you get an oscillation of the states back and forth.*

BF: *I just thought it would produce one scatter and not many.*

Fleming and her team hope to learn more about neutrinos by examining these neutrino oscillations. In particular, they are looking for muon neutrinos oscillating into electron neutrinos.

Their primary challenge is that, although neutrinos are extremely abundant, they are invisible and rarely interact with other particles, so they are very difficult to detect.

BF*: If you put your hand on the desk and you count to three, one, two, three, about a trillion neutrinos pass through your hand. They are being produced all the time in the upper atmosphere. They are hanging around, the relic neutrinos left over from the Big Bang. We can produce them here on earth. There are just copious amounts of neutrinos. Fortunately, you don't feel it because there are so many going through your hand. Unfortunately for a neutrino physicist, that they mostly stream through your hand makes doing experiments difficult because you have to build big detectors and very intense beams just to have a few neutrinos interact.*

In the 1990s, the Liquid Scintillator Neutrino Detector, or LSND, at Los Alamos National Laboratory, found evidence for oscillations from muon neutrinos to electron neutrinos, but in an energy range that was

unexpected.

To test these results, Fleming and a team at Fermilab designed a new booster neutrino experiment called "MiniBooNE."

> BF: *So this is MiniBooNE. This is the underbelly of the experiment. I think it looks like a giant ping-pong ball. MiniBooNE was designed to look for neutrino oscillations—looking for a muon type neutrino oscillating into an electron type neutrino.*

To run the experiment, muon neutrinos created at Fermilab are sent towards the MiniBooNE tank filled with 250,000 gallons of mineral oil.

> BF: *The good and the bad thing about neutrinos is that they mostly pass through everything, meaning we don't actually have to build a beamline directly to the detector. It's just sneaky little neutrinos sneaking in and sneaking out. But the bad part of that is we need many, many, many neutrinos to see just a few interactions in the detector.*

Most of the neutrinos pass through the MiniBooNE detector just as they would through any other matter, but occasionally one interacts with the atoms in the mineral oil.

When a muon neutrino hits an atom, a muon is released. Or if a muon neutrino has oscillated into an electron neutrino, an electron is released. While the team cannot directly detect neutrinos, they can detect these particles created from the interactions.

As the muon or electron travels through the mineral oil, they produce shockwaves of light called "Cerenkov radiation."

> BF: *Cerenkov radiation is a great phenomenon that is the mechanism that we use for particle identification on MiniBooNE. Einstein tells us that nothing can travel faster than the speed of light. But, you have to be careful. What Einstein tells us is that nothing can travel faster than the speed of light in vacuum. Light can slow down in media. In the oil that is in the MiniBooNE detector, light actually goes slower than the electrons and the muons that are produced from neutrino interactions. Those particles can jump out of their own light cone. And, just like you can get a sonic boom when you jump out of your sound cone, you can get a sonic light boom when you jump out of your light cone.*

The Cerenkov radiation sends a ring of light to the edge of the detector that is picked up by photomultiplier tubes.

BF: *This is a mockup of the inside of the MiniBooNE detector filled with 1,500 of these photo multiplier tubes. So, how do these photo multiplier tubes work? Basically what it is, is a light bulb in reverse. Where for a light bulb you put a current in and out comes light, for a photo multiplier tube light hits the face of the tube and out comes a current.*

With this data, the team creates an event display, which helps determine if the muon neutrinos have oscillated into electron neutrinos.

BF: *So the key is telling the difference between an electron and a muon and we do that by the Cerenkov signature they produce in the detector. So, an electron is a very light particle compared to a muon, so when it travels through the detector, it produces Cerenkov radiation but only for a short period of time. And it scatters around like a ping pong ball while it does it. So, it produces a light, fuzzy ring, which looks like the ring you see here. By contrast, a muon is a like a bowling ball in the detector. It Cerenkov radiates for a long period of time and so it has a filled in ring with a sharp outer edge. And a good example of that is this one shown here; there's a sharp outer ring and it's filled in. So really we're looking for open, fuzzy rings versus sharp, filled-in rings and that tells us electron versus muon.*

BF: *So this is the target. Let's pull up the water level.*

After analyzing their data, the MiniBooNE team did not find the high-energy neutrino events that the LSND saw. Instead, they found their own baffling oscillation results - that looked like electron events at low energies.

BF: *On MiniBooNE we've seen this puzzling result. We have about 100 events at low energies that we don't understand. We didn't expect to see it. We were looking for a neutrino oscillation on MiniBooNE, but at slightly higher energies. And when we opened up the box and looked at the data we were surprised to see no oscillations at higher energies, but these funny events at low energies.*

These low energy electron events could be interpreted as uncovering new neutrino physics.

BF: *You have to invoke new beyond the Standard Model physics, new neutrinos, new forces, new mechanism, instead of neutrino oscillations, to be able to explain both the low energy results seen by MiniBooNE and the LSND signal.*

But, the team could not confirm that their results were definitely electron events and not photons from an unexplained background source.

> BF: *So, with MiniBooNE we have this really interesting result but the MiniBooNE detector cannot differentiate electrons from photons. So, we're going to have to build a new kind of detector, a different kind of detector, put it exactly in the same place as MiniBooNE, looking at exactly the same beam, and one that can differentiate electrons from photons.*

In order to get more conclusive results, the team designed a new prototype detector called ArgoNeuT, which stands for Argon Neutrino Teststand.

> BF: *So this orange container contains ArgoNeuT.*

Instead of mineral oil, ArgoNeuT contains liquid argon, in a type of detector called a "time projection chamber." These liquid argon detectors can provide high-resolution images and have excellent background rejection.

After the initial collision of a neutrino in ArgoNeuT, the resulting charged particles drift to the edge of the detector, where they induce electric currents in a grid of tiny wires. By analyzing these currents, the ArgoNeuT team can reconstruct the path of the particles.

> BF: *We actually get a beautiful shadow of the event that we can read out from the edge of the detector. And here's an example of one of those events. The neutrino came in from this direction where you see nothing. And then you see a whole bunch of different particles flying off that you can reconstruct line by line in order to tell you what the event looks like. So, it's a picture; it's a perfect picture of the event.*

For each track, the team can measure the energy associated with it and identify the particle that created the track. It will also allow the team to differentiate between electrons and photons, something they couldn't do with MiniBooNE.

> BF: *It allows you to have millimeter precision as opposed to tens of centimeters of precision in terms of spatial resolution, and it allows you to differentiate electrons from photons mostly because you have that really fine-grained resolution.*

The team hopes to use ArgoNeuT as a stepping-stone to developing larger liquid argon detectors that could help confirm or refute the MiniBooNE results and be the key to a better understanding of neutrinos.

> BF: *I get to build detectors and collect data, all contributing to understanding the fundamental particles of the Universe. That's fantastic.*

Part II: The Search for the Higgs Boson

Mark Kruse

While Fleming continues to examine neutrino oscillations, Mark Kruse, of Duke University, is also working at Fermilab, searching for a particle predicted by the Standard Model that has yet to be observed: the Higgs boson.

> MARK KRUSE: *We've always been looking for the Higgs here. The discovery of the Higgs boson would fill out the Standard Model.*

First proposed in 1964, the Higgs boson plays a unique role in the Standard Model. It helps explain a physics mystery: how do fundamental particles obtain mass?

> MK: *We're looking for the Higgs boson as a way to explain the fundamental mass of particles***.** *You've got to have some mechanism by which that mass is generated. And the Standard Model does that most easily by what's called the Higgs mechanism.*

The Higgs mechanism proposes that the whole universe is filled with a field, called a "Higgs field." And particles obtain mass when they interact with this field.

> MK: *How easily particles go through this Higgs field is what we ascribe to the mass of that particle. You can think of a ball bearing going through molasses. It struggles to go through and that gives it an effective mass. Now, the more a particle struggles to go through the Higgs field, the greater the mass of that particle.*

According to quantum field theory, every field has an associated particle that manifests itself as vibrations in the field. So if the Higgs field exists, so too must its corresponding particle, the Higgs boson.

Detecting the Higgs boson would provide evidence for the existence of the Higgs field and the Higgs mechanism.

> MK: *The Higgs boson is essentially just a manifestation of the Higgs mechanism~~.~~ And so it's the missing piece in that if we find*

the Higgs boson, that gives some credence to this mechanism by which all other particles can acquire mass.

Finding the Higgs boson is not easy.

The Higgs is believed to be a relatively heavy particle, over 100 times heavier than a proton. Because it is so heavy, it decays quickly and therefore must be created in a controlled experimental setting to detect it.

Producing these heavier particles requires an enormous amount of energy, so physicists turn to large particle accelerators.

Kruse and the team at Fermilab are looking for the Higgs boson using the largest particle accelerator in the United States, the Tevatron.

The Tevatron accelerates protons and antiprotons very close to the speed of light in a 6 km underground ring, reaching energies up to 1 Trillion Electron Volts, or 1 TeV, thus the name Tevatron.

MK: *We're looking out on the Tevatron main ring. So this is about 4 miles in circumference. We've got beams of protons going this direction and the antiproton beams going in the other direction.*

The hope is that a collision of protons and anti-protons would create a Higgs boson.

The collisions take place in one of two detectors of the Tevatron called the Collider Detector at Fermilab, or "CDF."

MK: *OK, so we're about to enter the collision hall for the CDF detector. This is it. Most of the CDF detector you really can't see. Basically, bunches of protons are being accelerated by the Tevatron. They come from this direction. Bunches of antiprotons come from the other direction and they meet in the center of the CDF detector.*

These collisions occur millions of times every second. When they happen, the mass and energy of the protons and antiprotons gets converted into a spray of decayed particles.

MK: *Once you have a single collision, you've produced a lot of energy and from that energy you can get basically anything that's kinematically allowable. Basically, all they have to do is conserve energy. So from Einstein's equation, $E=MC^2$, if you've got energy, then you can produce any type of particle with a certain mass as long as the mass is less than the energy that you've created.*

That's why you want to collide protons and antiprotons at higher and higher energies. The higher the energy you collide them with, the greater the chance of producing heavier and more exotic types of particles.

The Fermilab team hopes these collisions will produce a Higgs boson. But the odds are not in their favor.

MK: *To produce a Higgs boson from a proton/antiproton collision is extremely rare. Only one in every trillion of those collisions will produce a Higgs boson. So, there's a lot of filtering that has to be done to actually extract the Higgs boson.*

Another challenge for Kruse and his colleagues is that, because the Higgs is so heavy, it quickly decays into other particles.

MK: *The Higgs boson decays immediately and it decays into other particles and it's those other particles that we then detect with this very complicated detector.*

Weighing 4,500 tons and standing over 6 stories tall, the CDF detector catches these particles and measures their energies.

To do so, the CDF has three layers of detectors.

MK: *The innermost detectors are the tracking chambers to measure the momentum of particles. Outside of that are the calorimeters. These calorimeters are in some sense like a thermometer. They just measure all the energy. And then outside of that are the other tracking detectors to measure muons. And so the general philosophy is basically just these three components to measure the final state particles that occur from these collisions of protons and antiprotons.*

JACOBO KONIGSBERG: *So, if you look here, this is an end-view of the detector.*

The team can identify these particles by examining the event display. Each particle created in the collision has a signature "look" within the tracking chamber, calorimeters, and muon chambers.

One example of a particle they might find is the electron.

MARK KRUSE: *So, you can see what we have here is a very high-energy track. It's very straight, which means it didn't bend much in the magnetic fields, which means it has a lot of momentum and a* *lot of energy. And then it deposited all its energy in the electromagnetic calorimeter. There's nothing else that looks exactly like this signature. So, this is a very good candidate for an electron.*

JACOBO KONIGSBERG: *It seems like it's coming down now. Or no?*

While particles such as electrons can be directly measured by CDF, the Higgs boson cannot. Because the Higgs decays so quickly into other particles, Kruse and his team must find evidence of the Higgs by looking for particles that are part of its signature decay.

MARK KRUSE*: That produces some complications because depending on how heavy the Higgs is, it will decay in different ways. And so therefore we have to search for it in different ways.*

Although the exact mass is unknown, recent research has determined that the mass of the Higgs is most likely between 115 and 160 GeV.

And, depending on its mass, the decay of the Higgs is different.

If the Higgs is relatively light, around 115 to 120 GeV, then its predominant decay is into two bottom quarks.

MK: *If the Higgs boson is light, most of the time it's going to decay to two bottom quarks. A quark won't just produce a single track. It will produce a lot of tracks and a lot of energy in the calorimeter.*

Unfortunately, this most frequent decay does not leave a very distinct signature in the CDF detector.

MK: *When it decays to a bottom and an anti-bottom, that's a very difficult event to distinguish from a lot of other very, very common events. And so we have to rely on other ways that the Higgs is produced.*

Although much more rare, a lighter Higgs may also be produced in ways that result in more distinguishable decays.

For instance, if the Higgs were produced along with a Z boson, the team would see a bottom quark pair from the Higgs decay along with a high-energy muon pair from the decay of the Z boson.

MK: *So, this is a very nice candidate for a Higgs boson event where the Higgs was produced in association with a Z boson. The Higgs has decayed to two bottom quarks, which wouldn't really stand out* *from a lot of backgrounds if it didn't have anything else in the event. The fact that it has two very high-energy muons in the event really does distinguish it from a lot of other processes.*

While this event may be a Higgs event, the team must gather more data before they have any conclusive evidence.

MK: *We can't ever just look at a single event and say this was due to a Higgs boson. And so we have to build up enough of these events to convince ourselves that the probability of some of these events were Higgs events is now quite high. And we can declare that we have evidence for the Higgs boson.*

In their quest, Mark Kruse and the Tevatron team continue to refine their methods and accumulate more data.

MK: *A lot of different people with a lot of different ideas are coming in and offering new analysis techniques, more advanced statistical techniques to analyze the data, and so that every possible way that Higgs could be produced and every possible way it can decay, all those possibilities are now being covered and all being combined together in a single Higgs boson search.*

The work at the Tevatron is not the final step in the pursuit of the Higgs. The search is being handed off to a team at CERN in Switzerland where they are able to produce more collisions at higher energies using the largest particle accelerator in the world: the Large Hadron Collider, or "LHC."

MK: *A lot of the experience that was developed at the Tevatron is going to be invaluable to continuing the searches at the LHC. And so, in some sense we will be handing over the baton to the LHC to determine what exactly was found at the Tevatron. It's going to take the LHC to actually measure the properties of what we've found at the Tevatron to determine if those properties are consistent with the Higgs boson of the Standard Model.*

Both Mark Kruse and Bonnie Fleming are working to fill the holes in the Standard Model with hopes of having a more complete understanding of the tiny building blocks that make up our universe.