Neutrino and Gen IV reactor systems
Prof. Jonathan Link, Virginia Tech, USA

Berta Oates
Doing today's introduction is Dr. Patricia Paviet. Dr. Paviet is the Group Leader of the Radiological Materials group at Pacific Northwest National Laboratory. She is also the Chair of the Gen IV International Forum, Education and Training Working Group. Patricia?

Patricia Paviet
Good morning. Thank you very much, Berta. It's a pleasure to have Professor Link with us today to give this webinar. It's funny because this week we have the American Nuclear Society meeting. I met Professor Link a year ago during that meeting. So, thank you again for volunteering to give this webinar. Professor Link is Working at Virginia Tech University as a faculty member. He is in the department of Physics since 2006. He received his Ph.D. in Particle Physics from the University of California Davis in 2001. He was a postdoctoral fellow at Columbia University. He has been part of several experimental collaborations including the Daya Bay Reactor Neutrino Experiment for which he shared the 2016 Breakthrough Prize for Fundamental Physics for his contribution to the discovery of the final neutrino mixing angle.

Currently, Professor Link is leading an effort to develop a new reactor neutrino detector technology known as CHANDLER which recently published their first observation of reactor neutrino. The prototype detector used in this study was one of the world's smallest neutrino detectors and the first mobile reactor neutrino detector. Professor Link is a member of the executive group for the NNSA-funded NuTools study which seeks to examine the potential for applications of neutrino detections to nuclear non-proliferation and the nuclear industry.

Again, thank you so much, Jonathan. I cannot wait to listen to your presentation. I give you the floor. Thank you.

Jonathan Link
Thank you, Patricia, and thank you Berta. It's great to be here today with all of you. Let's see if I can see the slides move. Here we go. A quick, sort of, not quite outline of the talk because it won't be quite this linear, but this talk will cover the history of neutrinos and reactors which is I think a long and interesting history. We are also going to talk about possible applications of neutrino detection. Then, I'll talk about advances in neutrino detector technology. But before doing any of that, I do have one disclaimer that I need to make.

And that is that I am a particle physicist, not a nuclear engineer. We physicists imagine ourselves to be quite clever, but we can be surprisingly naïve about the real world. We do hope, or at least I can say, I hope, that our technology can help to bring about a low-carbon future by enhancing the safety, security, and/or the efficiency of nuclear power. But none of us, that is none of us physicists know really how neutrinos could best be used in the nuclear industry. As a result, we need your help. That's the point of this talk. It's to raise awareness within the Gen IV community about the information available through reactor neutrino detection and the relative ease or difficulty of extracting that information. My hope is that this community, that is the Gen IV community, can help to identify appropriate problems where neutrino detectors may be a constructive part of the solution.

With that disclaimer out of the way, let's talk about the invention of neutrinos. 'Invention' is sort of a strong word here. Of course, they were a part of nature. They were just sort of postulated first by Wolfgang Pauli who is perhaps best known for his exclusion principle. He first proposed neutrino in 1930 in a sort of a 'desperate attempt' in his own words to save energy conservation and nuclear beta decay. At that time, they envisioned beta decay in this way. You have something like a bismuth-210 decaying to polonium-210 and emitting a beta particle which we now know as an 'electron.' With the two-body final state like this, conservation of energy and momentum would tell you that you expect to see the energy of that beta particle to be fixed, have the same energy every time at the Q value of the decay. But in fact, what was observed instead was a continuous spectrum that looks something more like this, we now know as the 'beta decay spectrum.' What Pauli's inspiration was, that if you added a third particle in the final state, that makes it possible for the beta decay to have energy less than the maximum – any energy, I should say, less than the maximum. In other words, you would get this continuous spectrum that was seen. And that particle came to be known as the 'neutrino.' We indicate the neutrino with the Greek letter 'nu.' As you see that throughout the talk, you will know what I am talking about there.

Now, in order for this particle that had never before been seen, to go unseen, it had to have no charge. It had to have no mass or at least very little mass and also a very weak interaction strength. In other words, it was a completely new and unknown type of particle which at that time was actually quite a daunting thing to propose because there were only two known subatomic particles, the proton, and the electron. So, this was increasing the number of particles by 50%. And the sort of more important thing was that this particle, this sort of what they thought was almost an accounting device, would be nearly impossible to detect.

In fact, it took 26 years for the neutrino to be discovered. The discovery experiment was led by Fred Reines and Clyde Cowan. They took detector to the Savannah River's P Reactor, which is shown here, with one of the world's least accessible historical markers. You can see Fred Reines on the left there and Clyde Cowan on the right in this picture of them in their control room in 1956.

Now, why go to a reactor to discover neutrinos. Well, reactors, it turns out, are an intense source of a type of neutrino called the 'electron antineutrino.' They come from the beta decay of the neutron-rich fission fragments. If we look at a typical fission here, uranium-235 might fission cesium-140 and rubidium-94 plus two neutrons. Now, these isotopes fall below the line of stability on this table of nuclei, it's here, you can see. They each have to beta decay. In fact, each of these will beta decay three times to get to stable nuclei. I've shown this one because, in fact, the typical number of beta decays or the average number of beta decays perfusion is about six, and in this case, three and three. Now, if you run the numbers on that, if you have 3-gigawatt thermal power reactor, that will produce $6X10^{20}$ electron antineutrinos per second. So, that's a pretty intense source of neutrinos.

Neutrinos, they are emitted isotopically. Their intensity falls off as one over the distance away from the reactor squared. So, the closer you are, the more neutrinos you see, and growing inversely to the square of that distance. They are so weakly interacting that they are completely unaffected by shielding. They will go all the way through shielding shown here, this containment dome, but will also go all the way through the earth, and they will go all the way through a million [ph] or a stack back-to-back without having a very high probability of interacting. But there is a probability it's non-zero. They carry information about the fission in the core like the reactor power, the spatial distribution of fission, and the mix of fissile elements that are present. And that information is unmolested by any shielding so you can actually interpret that at some standoff. With enough detector mass, in fact, you could track burn-up from outside secondary containment or even outside the security perimeter. And this tracking, importantly, it requires no input from the operators, it has no input on reactor operations. Of course, you can probably do more with collaborative input, but it's not required in order to interpret what the neutrinos are telling you.

So, how do we detect these neutrinos? As I say, they are very weakly interacting, but still they do interact, and they interact through a process known as 'inverse beta decay.' At least, that's the easiest way to detect them. In that case, we have a neutrino interacting with a proton, an electron antineutrino, and it's exchanging charge with that proton to create a neutron and a positron. This process has 1.8 MeV threshold. We typically use organic scintillators because the hydrogen nuclei in those hydrocarbons contain a lot of free protons for this interaction. Inverse beta decay results in a delayed coincidence signature which is very good for removing background as we'll see in the slide. The positron is detected promptly while the neutron thermalizes before it's captured, resulting in a delayed signal. In an undoped scintillator, the neutron will capture on hydrogen, but often the scintillator is doped with things like gadolinium or lithium-6 that enhance the capture.

Let's talk more about those backgrounds. The weak signal from neutrino interactions can easily be overwhelmed by cosmic rays and other conventional radiation. What I have shown here in this picture is detectors that are Daya Bay Reactor Neutrino Experiment. As you can see, this is in an underground cavern. It's about 450 meters underground and that's to stop the cosmic rays or at least reduce them quite significantly. Then, the detectors themselves are surrounded by layers of low activity shielding material. In this case, there are 2 meters of ultra-pure water on all sides of the detectors to stop that gamma rays from the rock. The delayed coincidence eliminates the vast majority of these backgrounds though. So, unless you get two things happening in close coincidence, you don't have to worry about them as a background. The remaining backgrounds are things like random coincidences where you get something that looks like a positron and something that looks like a neutron in the correct ordering. Then, also, particularly on the surface, you have to worry about cosmic-ray fast neutrons. Fast neutrons can form that coincidence signal by hitting a proton in the scintillator, which causes that recoil which mimics the positron. Then, following that, the coincidence will be completed by the neutron thermalizing and capturing in the detector.

Again, one more look at these backgrounds. We have nice ways of getting rid of the random coincidence. They have no structure in the time separation. This is a delayed coincidence but there is no correlation between the two events for a random coincident event so therefore there is no structure. We see on this figure here is this flat background beneath an exponentially decaying contribution that comes from the correlated events. Now, the correlated events here include both the fast neutrons and inverse beta decay and that's sort of an exponentially decaying time for the neutron capture. As a result, the fast neutrons are really the more serious background concern. If you don't have the ability to go deep underground, they can be a quite dominant source of background for you.

Back to the discovery experiment. Reines and Cowan used a layered detector, sort of like a club sandwich. They used it to pick out the specific signatures of the positron and neutron from inverse beta decay. In this case, the bread of the club sandwich shown by these tan boxes is a liquid scintillation detector, whereas the neutrino target are these blue boxes which is a passive target. So, it's not instrumented to detect anything. Now, what they wanted to do to get rid of the fast neutron background in particular is they wanted to focus on a specific signature of the positron and also have a distinct signature for the neutron. So, they are looking for that delayed coincidence. But when a neutrino interacts in this water target which is water with cadmium chloride in it for neutron capture on cadmium, they only see the positron annihilation. A positron will come to rest. It will find an electron. It will annihilate. You get two 511-keV gammas. A lot of the time, given the fact that the target is fairly thin, those two gammas will go off into the opposing liquid scintillation detectors on opposite sides of the target. Similarly, for the neutron capture, because you get a spray of gamma rays with capture on cadmium, you'll often see gammas in both sides as well. So, you are looking not only that coincidence in time but also the coincidence between the detectors above and below the target. Now, by tagging the positron annihilation in this way, they were able to filter out a lot of the fast neutron backgrounds which actually made their neutrino detection possible.

Now, since their discovery experiment, there has been a long history between neutrinos and reactors. Dozens of distinctive reactor experiments have been performed. Among other things, reactors have been used to study different types of neutrino interactions, searched for things like the neutrino magnetic moment which hasn't been found yet, searched for and then ultimately studied neutrino oscillations. I've highlighted 'neutrino oscillations' here because actually this is really the most important discovery in particle physics in the last 40 years. This is where reactor neutrinos have made their greatest contributions to science. Well, now that I say that, obviously, discovery of the neutrino was quite an important contribution to science. But since then, it's been in the studying of neutrino oscillations. Now, if anyone here knows about the Large Hadron Collider, they may question my calling neutrino oscillations the most important discovery in the last 40 years. But in fact, this is really – whereas the Higgs boson was a particle what we call the standard model of particle physics which was discovered in 2012 with the Large Hadron Collider, neutrino oscillations were actually not part of that framework and therefore I think were a more significant discovery.

But anyway, I'll leave that to the debate of historians of science in the future. But before discussing neutrino oscillations, it's really important to do a quick introduction to particle physics.

Particle physics is the study of fundamental particles and forces. There are four fundamental forces. We have gravity, we have electromagnetism. There is also the strong nuclear force which holds the nucleus together. And there is the weak nuclear force which is responsible for nuclear beta decay. Neutrino interactions are weak because they only feel the weak nuclear force. Parenthetically, I'll mention, now that we know they have tiny masses, they will in fact feel the gravitational force. But the gravitational force is so small on the scale of particle physics on the microscopic scale of particle physics, that it's irrelevant and not really a part of the particle physics framework.

Those are the forces. Now, let's talk about the particles. This is the table of the fundamental particles that we know and that are part of our standard model of particle physics. There are 12 spin-1/2 particles. They include the 6 quarks and the 6 leptons. The neutrinos are part of the leptons. All of these spin-1/2 particles are charged with the exception of the neutrinos. There are actually three neutrinos. All of these particles in fact come in three generations. And the generations get progressively heavier; otherwise, they have the same property. So, all the particles in a row here will have the same properties, just getting heavier from left to right. In fact, the matter that we know of and we experience in our everyday lives is all made up of this first generation. All the other particles are unstable with the exception of the neutrinos. As far as we know, all of the neutrinos are stable.

Now, beyond those spin-1/2 particles, there are spin 1 particles we call 'gauge bosons' which mediate the forces. The gluon, for example, mediates the strong interaction between the quarks. The photon mediates the electromagnetic interaction, it interacts with all of the charged particles. And then the Z boson and W bosons mediate the weak interaction and they actually interact with all of the 6 spin-1/2 particles.

Then, finally, there is the Higgs boson; this is the particle that was discovered by the LHC in 2012. And it's responsible for giving the other particles mass.

For each of these particles, there is an antimatter counterpart. We denote the antimatter with a bar over the top of the particle, at least for the spin-1/2 particles. The antimatter particles have opposites sign charge relative to their matter counterpart. Whereas the electron is minus 1, the positron, its antimatter counterpart is a plus 1 charge. The neutral bosons are their own antimatter particles. Well, these four, including the Higgs boson – these four, all their antimatter, the W boson comes in both W-plus and W-minus, so that's the antimatter for the W. For the neutrinos, even though they are neutral, we do have both neutrinos and antineutrinos. So, that's important to keep in mind that there is a distinction there.

One more thing to say about these particles is to talk about their masses. As I said, from the different generations we're getting heavier and heavier with the possible exception of the neutrinos which we don't actually know how those masses line up. We only have limits, upper limits on their masses. We do know they have mass though, as I'll talk about in a minute. But what's interesting about the mass here is that from the electron to the top quark which is the heaviest known particle, there are 6 orders of magnitude difference between the masses. But then there is a gap here that is about 7 orders of magnitude wide, at least, 7 orders of magnitude wide. And then you have the neutrinos. Having tiny masses that are not exactly zero is quite an interesting difference between interference [ph]. In fact, in the standard model of particle physics, the neutrinos were always assumed to have zero mass, until 1998, when we discovered that they oscillate.

Now, why does that tell us, they have mass? Well, if neutrinos have mass, then the three types of neutrinos are allowed through quantum mechanics to mix with each other in a sinusoidal pattern. Why? What does that mean? This is an example of what that might look like. What I am plotting here is the probability of a neutrino that starts out as electron antineutrino, acting like an electron antineutrino at some later time. We are plotting this as a function of the distance the neutrino travels, that's L, divided by the energy of the neutrino. But if we take the mean energy of a reactor neutrino, say, we could plot this just as a function of distance. All right. There we go. I should have animated that first. But what does the neutrino become when it's not an electron antineutrino. Well, here, I plot in yellow, the probability of a neutrino that starts out as an electron antineutrino, acting like a muon neutrino. Of course, that's zero at the beginning, but at some later time it will reach a maximum. If we take up all the things that the neutrino can become and add them up, the total should always be one because it's always a neutrino, but it's not always an electron antineutrino like it started out as. In fact, at some point it will be very much unlike an electron antineutrino, but it will go back to being a 100% electron antineutrino at some later time. Inverse beta decay, this is the process by which we see the reactor neutrinos. It's only sensitive to electron antineutrinos. This is important because – to answer this question, so what does it mean for one of those neutrinos to act like a muon antineutrino or a tau antineutrino. It means that we won't see it in our detector. And that's all that we know. What we have when we are studying oscillations with reactor neutrinos is we have a disappearance which has this sinusoidal dependence on distance and energy.

Now, this is a plot of the actual parameters that we have. Electron neutrinos and antineutrino undergo two types of oscillations. The different oscillations, they are characterized by amplitudes and periods. The amplitudes tell us about the strength of the mixing and the period tells us about the masses of the neutrinos. And here I've plotted – this is the function of the mean energy for detected reactor neutrinos so that we can actually get a sense of the distance scale for this oscillation. For example, there is a short-baseline oscillation that has its first maximum at about 2 kilometers away from the reactor. And then there is a longer baseline oscillation that has its first maximum at 60 kilometers from the reactor. And of course, reactor experiments have made critical measurements for both types of electron neutrino oscillations.

I’ll start off by talking about the KamLAND experiment. This was a very interesting experiment that was done in Japan in the early 2000s. They used neutrinos from all the reactors in Japan and South Korea and Russia and in fact potentially, from around the world, but since the flux is following off as 1/r-squared [ph], it's really the regional reactors that were important here. KamLAND measured the long-baseline oscillation period. This oscillation had previously been observed using neutrinos from the sun or what we call solar neutrinos, but because the sun is so far away we couldn't really get very good measurement of the period of oscillation. What we are seeing here is the data. The black dash line, I think they are normalized distribution, but this is the shape of distribution you would expect if there were no oscillations. Instead, this blue line was observed. You can actually see – well, the blue line is the best fit to the database. You can actually see the black data points here showing that there is a deficit of neutrinos observed that’s quite significant here.

Beyond KamLAND, there was the Daya Bay Experiment. This Daya Bay Experiment ran earlier in this past decade. I was a part of this experiment. We studied short-baseline oscillations. In fact, these oscillations had not been observed before we made that first observation. We also measured the smallest oscillation amplitude to what is now the greatest precision, showing the power that reactor neutrinos really have. This is the layout of the site. As I told you, the short baseline, you expect the first oscillation maximum to be at about 2 kilometers. So, this far site is actually about 1800 meters away from the reactors, it's 1600 to 1800 meters. There are actually six reactors at the Daya Bay site. Because we don't understand the reactor flux that well and we want to make a really precise measurement, we knew if there was something to measure here, it was going to be very small. We had to use near detectors to measure what was sort of a proxy for the un-oscillated flux. So, you get close to the reactors, you can sort of see it before there has been a lot of oscillations. These were the detectors that we had in our far site. We’ve already seen these. But there were four detectors each with 20 tons of gadolinium-loaded liquid scintillator. And this is what we saw. Without oscillations, we expected the red histogram here. With oscillations, you can see our data, the black lines. Very precise. You can barely see the air bars or not at all actually. It's fitted to what we would expect by weighting what we observed in the near reactor. There is a quite significant deficit here in the middle of the spectrum.

In addition to measuring oscillations, the Daya Bay Experiment has actually taught us quite a bit about reactor neutrinos and things that will be very important for potential applications. So, let's move on to start talking about those things.

First, you need to know that the neutrino spectrum will evolve as the fuel burns within a reactor. If you are talking about a low enriched uranium reactor, as the fuel burns the mix of fissile isotopes will evolve. Here you see, it starts out at about 75% uranium-235 for a clean core. At the end, it's down to about 50%. Whereas the plutonium has grown here, 239, from about 15%, up to about 40%. And Pu-241 has also grown but it's a subdominant contribution. Now, I am sure you've all seen this graph before but of course each fissile isotope makes a slightly different set of fission fragments. Because you've got more nucleons and the heavier isotopes, so you wind up being higher up on the atomic mass number scale here, particularly in the lower lobe.

As a result, each one of these different isotopes will have a different beta endpoint. So, the neutrino energy spectrum could be like a fingerprint for the active mix of fissile isotopes in the core, just we have different contributions, different beta channels contributing to that spectrum. So, that's the theory.

Now, Daya Bay managed to do a neutrino spectral decomposition based on the burnup data from the reactor operators. We used neutrinos from one of our near detector sites to decompose the spectrum for the different fissile elements. Here you can see in blue the spectrum that we associated with uranium-235 in this decomposition. In red, this is the spectrum from the combined plutonium isotopes, although it's dominated by 239. The data confirms this fissile element fingerprint hypothesis. I'll note that this study was done with detectors located 363 meters away from two cores which were out-of-sync in their refueling cycles. If it doesn't look terribly precise, there is a reason for that. It was actually quite a difficult thing to do. But imagine what could be done with a detector at 25 meters which is primarily single core dominating the neutrino flux, so you are not having a mix of two cycles involved. It actually can be done, I think, significantly quite better than this

Let's talk about the functionality that may be useful for applications. As we just saw, the neutrino detectors can track a reactor's active fissile inventory. We can track burnup, and that could be useful. In addition, the neutrino detection rate measures the reactor power. I should note here that this is really something that could be averaged over hours or days but probably not over seconds. It's not going to be used to scram a quick, a momentary overpower on a reactor. This is not the tool for that. An array of neutrino detectors may be able to measure the spatial distribution of fission by triangularization. That information is certainly in there. Neutrinos can be used to detect when a reactor is on. This is sort of obvious. But maybe not so obvious is that this can even be done at a significant stand-off. So, those are the things that could be done.

Now, again, I'll remind you of my disclaimer when I talk about applications that we've sort of uncovered or thought of as physicists. But, certainly we've long thought, reactor neutrino detectors would find applications in reactor monitoring. Therefore, we've done a lot of things to sort of promote that idea. There has been this Applied Antineutrino Physics Conference Series which has been going on annually since 2004. Unfortunately, it's now, at least, mostly physicists talking to each other. And that I think probably needs to change.

This year, the NNSA's Office of Defense Nuclear Non-proliferation has commissioned the ongoing NuTool study. You can see the webpage there. Please do visit that. The goal of this was to engage with experts in the nuclear industry and in nuclear security to assess the viability of possible applications. Then finally, last spring, I led a team here from Virginia Tech in a study of 'possible applications' funded by the National Science Foundation's Innovation Corps. I just want to talk about that for a minute.

Maybe some of you are aware of this program, but NSF's I-Corps program gives inventors training and money, academic inventors typically, training and money to gather data on commercialization of their technologies. Participants have 7 weeks to dash around the country and interview more than 100 people. In fact, that's a requirement that you interview at least 100 people in the appropriate industrial sectors. This is actually a map of all of the places we physically went to and talk to people at all of these different institutions. In fact, hopefully, some of you are on the call.

Now, here are some of the things that we actually identified through these various processes I just discussed. In the context of nuclear non-proliferation safeguards, several possible applications have been identified. Recovery from a loss of continuity-of-knowledge event. After possibly a diplomatic break or other interruption in monitoring, neutrinos can determine if plutonium has been removed from the reactor, or at least the status of the reactor is as reported by the entity being monitored. Another possibility is, we could do continuous monitoring of a reactor's operational status. As an example, within the context of the JCPOA, Iran's heavy water reactor was rendered inoperable instead of just shut down. But, in future agreements a party may not agree to that condition and neutrino detectors could instead be used to ensure that a reactor remains off for the duration of an agreement without it being destroyed.

Then, of course, tracking of fissile inventory in operating reactors. This is something we discussed with this fingerprint hypothesis. This may enable verification for possible future agreements like Fissile Materials Cut-off Treaty. So, that's in the context of safeguard.

But what about just reactor instrumentation? Potential applications we've identified here include things like neutrino calibrated ex-core neutron detectors or multi-modal detectors, neutron, and gamma potentially. But let's talk about neutron detectors. For example, inverse beta decay detectors are also excellent neutron detectors because we need to tag those thermal neutrons for the inverse beta decay. The question is could ex-core neutrino detectors eliminate the need for in-core neutron detectors and thus significantly reduce the number of pressure vessel penetrations in a reactor. Of course, tracking of the fissile inventory is something we've discussed. But it may have particular relevance for Gen IV reactors, particularly those without fixed fuel. People talk about doing things like chemical assay, but that creates a waste stream, and also sample pulling becomes a proliferation risk.

Neutrino detectors could be a low-risk alternative for continuous monitoring of the burn-up. Then, finally, verifying the critical status of a core following a beyond design basis accident or incident. I should start saying, 'God forbid.' In fact, we hope that this never does happen, but that doesn't mean you don't prepare. If there was an accident and the plant's instrumentation goes offline, neutrino detectors could be used to determine if there is active fission reaction going on in the core.

What do we have to do to make these applications a reality? It's a difficult problem. Nuclear security and non-proliferation safeguards, in situations with limited trust they have always seemed like a good starting place, at least to physicists, for applications. But perhaps not for the IAEA. Understandably, the IAEA is reluctant to express a mission need requiring nonexistent or unproven technologies. Similarly, for existing commercial reactors they have all the instrumentation they need to satisfy the regulatory requirements. Gen IV reactors, they may have unique needs, and in particular because they are not already built and in many cases not received full regulatory approval, there may be an openness to innovative new solutions.

Finding use cases in commercial nuclear would help us to establish neutrino technologies for security applications. I'll refer you back to point-2 here which is if we can find a way to use this in commercial nuclear, then it can be acceptable perhaps for monitoring and safeguards.

One of the issues that need to be resolved is actually finding a detector technology that will do the job. So, it's worth talking about what has come before and what that means. So far reactor neutrino detectors have been mostly delicate research instruments, requiring ideal conditions and constant attention. It's not really what you need for instrumentation. They typically use liquid organic scintillators which tend to leak and have issues with long-term chemical stability. Also, particularly when they leak, problematically, they are flammable. These detectors are large and unwieldy. Imagine having to have a large cavern 450 meters underground every time you wanted to use neutrinos the monitor reactors, it’s not practical. They need the thickest possible overhead shielding to combat cosmic-ray fast neutron backgrounds. What this means is, as a result, they are either at some significant standoff in an underground cavern or perhaps constructed in situ in a tendon gallery which is not a practical solution. In fact, that's the point here. These detectors are not suitable for widespread use of applications.

But that's where the CHANDLER technology – I will note before talking about the technology we are developing here at Virginia Tech, that there are others working in this area. But I am going to talk about what we’ve been doing. CHANDLER was designed from the start as a robust mobile neutrino detector technology. What you see here is our MiniCHANDLER prototype. This is actually our largest prototype thus far. This is during its assembly. It would be shut up light-tight. But it shows you the construction here. We are using a highly segmented array of plastic scintillating cubes. You can see the cubes here. And those are the neutrino target and positron detectors. Then between those cube layers, there are thin sheets of lithium-6 doped zinc sulfide scintillator, and we used that to capture and tag the neutrons. The light in this detector is transported along the rows and columns of cubes by total internal reflection and readout by photomultiplier tubes or PMTs. You can see, one side here is constructed, and there will be another side here when it's fully assembled, or there is but not in the picture.

As with the Reines and Cowan experiment, the segmentation is being used to tag the gammas from positron annihilation, and thus reject the fast neutron correlated background. As you will see, that actually was quite successful.

After building this detector, we installed it in our mobile neutrino lab. You can see the detector here. The purple is boron-loaded poly for stopping thermal neutrons from the reactor. It was installed in our mobile neutrino lab and deployed to Dominion Power’s North Anna Generating Station here in Mineral, Virginia, and parked just outside their Reactor 2.

I have to just show this other perspective of that deployment. Here, this is from Google Earth. It may not be on Google Earth anymore, but at some point, not long after our deployment, I was checking out Google Earth and noticed that our mobile neutrino lab made the picture just outside their Reactor 2.

Let's talk about the data. We will start out talking about the fast neutron background. We are on the surface. It’s a totally unshielded detector. There was 1 inch of boron-loaded poly and a very thin roof to the trailer. But other than that, no shielding from cosmic-ray neutrons. So, the fast neutrons are a significant background. Here, we are plotting, as a function of time – I believe, these are hourly rates for random coincidence events here in blue, and then also correlated events which include both, the fast neutrons, and the inverse beta decay. But it's dominated by the fast neutrons here, in part, because – well, in large part, because we have not applied our positron tag on this sample. What the data shows is that the fast neutron rate is independent of the reactor power, or almost nearly so at least to the eyeball here. On the other hand, the random coincident rate has a strong dependence on the reactor power because about half of our random coincidence events involve a thermal neutron from the reactor. When the reactor is off, that rate drops by half. So, it's good to see we are not getting any reactor correlated backgrounds, at least not large reactor correlated backgrounds out of the correlated rate. Instead, the corelated rate is inversely correlated with atmospheric pressure, and that's just because it is dominated by fast neutrons. The higher the atmospheric pressure, the more shielding we have against atmospheric fast neutrons.

Now we can make the correction for that, and after doing that correction we found that the average reactor on correlated rate was 4 events per hour more than with the reactor off. In fact, that was the expected rate for reactor antineutrino events. Now, it's not shown here but even in this simple prototype the positron tag improves the signal-to-noise by a factor of about five. So, we are getting more than a 5-times reduction in this rather crude prototype, as you'll see in a minute.

What does that mean? MiniCHANDLER was really just a demonstration that we could see the neutrinos at all with this technology. It was simultaneously the largest detector we could afford to build and the smallest detector that we thought had a chance to see neutrinos. We used surplus photomultiplier tubes and we had to forgo the light guides that were shown to improve light collection's efficiency by 64%. We had no cosmic-ray shielding, as I've discussed, and only an inch of boron-loaded poly to stop the terminal neutrons from the reactor. And yet, we were successful in not only seeing reactors but also measuring somewhat crudely the reactor neutrino spectrum. With this successful observation, we became the first unshielded reactor neutrino detector, the first mobile neutrino detector, and the world's 3rd smallest neutrino detector, and 2nd smallest reactor neutrino detector ever.

Being small is not really an asset. We need to be larger in order to do to applications. But we think with this technology even refrigerator-sized detectors may be useful.

Let's talk about ways that we can make this detector better. To study the impact of adding modern PMTs and light guides, we rebuilt our smaller prototype. This is our Micro CHANDLER prototype. It's a 3x3x3 module. With half new PMTs that's shown on the top here, and including light guides, and then half old PMTs down here. We exposed this hybrid prototype to a sodium-22 source which has a 1273 keV gamma. Also, it's a beta plus source, so it has two 511 keV annihilation gammas from the positron. You can see the Compton edges in this detector because it's plastic scintillating cubes; it doesn't have full containment in a single cube, typically. On the left here is the old PMTs. On the right, we are showing the new PMTs with light guide. You can see, the resolution is improved by a factor of 2. You can see that very clearly around this 1273 keV Compton edge. But even more importantly, for the way in which we intend to remove fast neutron backgrounds, this 511 keV Compton edge from the annihilation gamma, it stands out much more clearly than it did with the old PMT. In fact, we believe that our positron tag will be vastly superior with these new optics. In addition, the planned upgrades will get us to the energy resolution and efficiency that are needed for a range of applications. What we are looking at here is doubling the number of lithium-loaded zinc sulfide sheets which has been shown to improve the neutron detection efficiency by 35%. Right now, it's about 50% of the neutron's capture on lithium-6. That will go up to about 70% with doubling of the sheets.

As I said, we need to increase the detector mass. It will be somewhere between 2 tons and 5 tons depending on the applications. With that, we can accumulate events at several hundred per hour and more effectively contain the neutrons and annihilation gammas. With that small MiniCHANDLER detector, a lot of the annihilation gammas and neutrons escaped off the sides. Also, our improved optics will include not only the new PMTs and light guides but also PMTs on four sides which will increase the signal-to-noise to better one-to-one while simultaneously sharpening the fissile-element specific spectral differences that are so important for applications.

So, what comes next? This detector R&D program is just getting started and there is more that we need to learn about the fissile-element specific neutrino spectra. To do this, we need to build a ton-scale detector using our best and most sensitive technology and use this detector to demonstrate the required sensitivity. The detector, once that’s been shown, we will deploy detector modules to a wide variety of reactor types to complete a high-resolution decompensation of the fissile-elements spectra. Light water commercial reactor is probably a good starting point but also highly enriched uranium research reactors to get a pure U-235 spectrum. A CanDU reactor may give us as a better measure of the U-238 spectrum, whereas a MOX fuel reactor would enhance the plutonium. I am also open to hearing from others where we should go to get better isotope-specific data. Then, the last point here is we need to continue to engage with the nuclear industry, with you all, to figure out how this technology can best be used.

I guess that brings me to my conclusions. From the original discovery experiment in 1956, nuclear reactors have played a crucial role in furthering our understanding of neutrinos. We physicists have hopes of giving back to the nuclear industry that has been so kind to us by developing reactor enabling technologies based on neutrino detection. Advances in neutrino technologies are pointing the way to robust instruments that can operate above ground and in the environment around an active reactor. The CHANDLER technology is one such detector and our R&D program seeks to demonstrate its full potential.

The last point here is, we need your help to identify promising use cases and to establish the performance requirements to meet those needs. I look forward to engaging with all of you in the future. Thank you.

Berta Oates
Thank you, Dr. Link. If you have questions, please go ahead and type those into the questions pane now. While those questions are coming in, we are going to just take a quick look at the upcoming webinar presentations. In December, a presentation on the 'Development of Multiple-Particle Positron Emission Particle Tracking for Flow Measurement.' In January, 'MOX Fuel for Advanced Reactors.' And in February, an 'Overview of Waste Treatment Plant, Hanford Site.'

Just a second. Joining us now is Dr. John Kelly [ph]. John, are you able to see the questions?

John Kelly
I don't see any question, Berta.

Berta Oates
What I am going to do is there is a question in.

John Kelly
You still there?

Berta Oates
Did it post for you? Did that come up for you on the chat pod? I sent it to you.

John Kelly
Let me go look. Hang on. I am not seeing the chat pod.

Berta Oates
Let me keep looking here.

Jonathan Link
Did you just post it to John or did you post it to all panelists?

Berta Oates
Let me see if I can post it to all of you.

Jonathan Link
Okay. Now I am seeing questions. Okay. Thanks. Okay. I am seeing a question here. I don't know, John, if you want me to address this, or you want to review it first, but under the question section. That disappeared.

Berta Oates
I was trying to send it to both you and John. It looks like I can send it to one or to the other.

Jonathan Link
Oh, you posted that one, Berta.

Berta Oates
Right. I just shared it as – assigned it is the terminology that they use.

Jonathan Link
Okay. Well, while we are working out the technology, should I just sort of read back that question that I saw and answer it. I think it seems harmless from what we…

Berta Oates
Yes. Let’s do that.

Jonathan Link
All right. The question was, “What about interference from neutrinos from other reactors?” It's a good question. In fact, we’ve looked at the potential of maybe adding neutrino detectors to a configuration of reactors like at the NuScale plant with 12 reactors on in one site, in one building. I did mention that it is possible to do triangularization. If you have an array of detectors looking at neutrinos, if you have a well-chosen array, in theory you could deconvolve the neutrinos coming from different locations by hitting different detectors against each other at appropriately chosen positions to be able to do that. In fact, that would be significantly easier than you would expect to, for example, do spatial resolution within a single core. For a typical site with existing reactors like at North Anna where there were two reactors, being 25 meters from one core, we were 75 meters from another core, it meant that about 7% of the neutrinos that we saw would come from the second core, but we were dominated by one core. In fact, we could have chosen a better location where we were more like 100 meters away from the second core. I think we were actually 90 meters. Anyway. We were not as far away from the second core as we could have been. There are things you can do to really focus primarily on a single core even in configurations where the reactors are

about 90 meters apart from each other. But there are definitely challenges associated with that. But I think they are manageable. All right. I am seeing more questions here.

The second question I see here is, "You mentioned atmospheric background sources. I would have assumed terrestrial sources from primordial distributed throughout the planet to dominate backgrounds. Why is this not the case for your system?"

Well so, there are neutrinos from uranium and thorium daughters, and also potassium-40. There are just a few of those that are above the 1.8 MeV threshold. They peter out by about 2.6 MeV. They were a meaningful background to KamLAND experiment which had an average distance from the reactors of 88 kilometers. If you are 25 meters from a reactor, that background from what we call in the business 'geoneutrinos,' it's really insignificant. They are present. They can be detected. In fact, people talk about taking these inverse beta decay detectors to locations like Hawaii where you have no reactor neutrinos and actually very little crystal [ph] neutrinos for that matter from the geoneutrino perspective and studying those kinds of neutrinos specifically. It's much harder to get the geoneutrinos out than it is to get the reactor neutrinos. There are just many fewer of them.

Let's see. You say, there are more questions, Berta, I am still only seeing two. Okay. So, the question is, "Who are industry partners for the CHANDLER detector?" We have been building up partner relationships. I don't want to in somebody who perhaps isn't necessarily ready to be declared a partner yet. But we have had support for some of our proposals that we've written from Terrestrial Energy in Canada. Also, Framatome and BWXT have supported us in proposals that required letters from potential industrial partners. We are working with Eljen Technology. It's a scintillator manufacturer in Texas that I think is very interested in a partnership largely because our detectors use an awful lot of their scintillators. We are definitely interested in building up industry partnerships, and particularly working with potential users – companies that are developing new reactors that could be potential users for this technology and figuring out how reactor neutrinos may be enabling for their technology.

Okay. Next question. "Do you see a potential application for monitoring microreactors, less than 20-megawatt thermal operation?" Obviously, as the power goes down, it becomes more challenging. The neutrino event rate goes as 1/r-squared, but also is linear in the reactor power. 20-megawatt thermal, I think we definitely would be able to see neutrinos at a pretty decent rate from a reactor like that. For example, for a lot of our studies, a basic neutrino physics, we have been interested in using small research reactors, more like 80 megawatts, like the High Flux Isotope

Reactor at Oak Ridge or the BR2 reactor in Belgium because these reactors, A) are highly enriched uranium reactors, and we need to measure that flux, neutrino flux. And also, because, for some oscillation searches – I mean I talked about two types of oscillation, but we actually have also been searching for oscillations in other baseline regimes, and in particular, very short baselines of, say, 5-10 meters from the core, have been subject of a great deal of interest to us scientifically. Having a compact core is important because, if your baseline is 5 meters and your core is 4 meters, you are really getting quite spread in your baselines within your detector that would smear out the oscillation effect. Indeed, below 20 megawatts is challenging but not impossible.

Berta Oates
That's all we have for now. For questions that you still have, go ahead and type those in. While we wait just a little bit if you have a few minutes to wait, Dr. Link, I am going to go ahead and thank you again for sharing your expertise with us today.

Jonathan Link
My pleasure. I can make a quick comment here while people are perhaps typing in additional question, and that is, just looking through attendees, it looks to be a fairly international audience which is excellent and may say a lot of the fact that the ANS meeting is going on in parallel for the US audience. Maybe it's worth talking, just mentioning some of the other efforts around the world. For example, I mentioned that we are the world's 2nd smallest reactor neutrino detector. There was another prototype detector from a Russian group that was 40 kilograms. Our MiniCHANDLER is 80 kilograms. Their detector, they called it dansino [ph] was located beneath one of the Kalinin reactors, and it was about 10 meters from the core. They were very close to core, much closer than our 25 meters. Remember, the flux is going as 1/r-squared, so that's a significant increase in the flux. Then, they were underneath the core which gave them about what we call 50 meters of water equivalent shielding which pretty much stops the fast neutrons dead unless you can create new fast neutrons from muon interactions and material above the detector. But with those conditions, they were able to have an even smaller detector than we used and successfully identifying neutrinos. So, that's one effort.

There is an effort in Japan. I think it's called ‘Panda’ that also has now used a mobile neutrino detector. I think we came first, but not far off our heels was this Panda effort with a mobile neutrino detector, and I don't remember the Japanese reactor it was operating at. I believe they also had plastic detector and were able to see the neutrino rate. I don't think they measured the neutrino spectrum yet. There is an effort in the UK. I believe it’s at the Wylfa reactor if I am saying that right called VIDARR. That's done by the University of Manchester group I believe. It's

Manchester or Liverpool. I think it's Liverpool. Anyway, by a group of UK scientists. They also have used a semi-mobile detector. It's in a shipping container. It's not on wheels but it can be delivered and dropped at a site. Their observation, again, of neutrinos, was fairly contemporaneous with ours. There are a lot of efforts that have been focused more on the neutrino science than on applications, but near detectors or detectors close to reactors, operating – I mentioned HFIR. There was an experiment at HFIR called PROSPECT which used a liquid scintillating detector and actually succeeded in showing the challenges with such a detector and that they had issues with leaking.

There were another couple of experiment on the continent in Europe. SoLid is an experiment at the BR2 reactor which is using plastic scintillating detector. It's actually very similar to ours, but instead of having their cubes – they use cubes and they used the zinc sulfide sheet as we do. In fact, we got that idea from them. But instead of having their cubes optically connected as ours are, they are using fiber readout running along the edges of the cubes. The cubes are optically isolated, but a fiber runs along the edges of rows and columns of cubes and gives them position information.

Let's see. There are no other questions still. So, anyway. Berta, I think if there are no other questions, perhaps – okay, I am seeing another question. Thank you. The question is "What is the time constant for neutrino detectors? Can it operate in real-time?"

It's a question of what you wanted to do and how much detector you want to build. As I said, you are probably not getting a good measure of power on the level of second, certainly not one that I would use to scram a reactor. But it's for immigrating over hours and over days. You can certainly do much better. Of course, you can always build a bigger detector. There is the question is what is practical and what's the cost.

Berta Oates
Thank you, again, Dr. Link, for your time and your expertise in putting this presentation together. It takes a bit of effort to do that. Thanks to everyone who joined us today. Dr. Kelly, Dr. Paviet, thank you very much for attending the GIF webinar presentations. I don't see any more questions coming in. We are just 5 minutes past the hour presentation time, so I think that was perfect. Unless there is a quick question to come in, I think I will wish everyone a safe and a good day.

Jonathan Link
All right. Thanks, everyone, for attending. Berta, for organizing this.

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