

Small Accelerators

by Janet Conrad



You can't see neutrinos, but they're everywhere. Our Sun emits more than 10^{30} of these elementary particles per year. More than 40 billion go through your thumbnail every second. There are approximately a billion neutrinos per cubic meter in all parts of space, left over from the Big Bang.

DESPITE BEING LITERALLY SURROUNDED BY THESE PARTICLES, we know surprisingly little about them. The problem is that the neutrino almost never interacts with matter. To give you a sense of this, a single neutrino from the Sun can travel through about 200 Earths before hitting an atom. They don't interact very often because neutrinos interact via the aptly named "weak force." This simple fact makes neutrinos very difficult to study. We don't know what the neutrino



for Big Questions

mass is, we don't know if matter neutrinos and antimatter neutrinos are inherently different, and we don't know how many neutrinos there are. These questions and more are not only relevant to describing the fundamental nature of matter from a particle physics perspective, they are also vital in gaining a deeper understanding of how the universe evolved. One needs a very intense neutrino source and a very large detector to observe a neutrino and measure its behavior. These are the great challenges in neutrino physics today, and MIT, with its emphasis on innovative technology, is playing a leading role in meeting them.

To study neutrinos under controlled conditions, scientists produce neutrino beams using proton accelerators. The protons are slammed into a target where they shatter and produce short-lived particles that decay into neutrinos. As these neutrino beams are man-made, physicists can control many important qualities, including whether the beam is made of neutrinos or antiparticles (called antineutrinos); the energy of the beam; and even the varieties of neutrino—which comes



FIGURE 1

A photograph of the Main Injector at Fermilab. Superimposed on this image, at the center, is a dot indicating the size of the DAEδALUS cyclotron, for comparison. [Courtesy of Fermilab VMS]

in three different types or “flavors.” The problem is that only a few accelerator laboratories in the world can produce beams with enough neutrinos for precision measurements. The Main Injector Particle Accelerator at Fermi National Accelerator Laboratory is one. This machine accelerates protons up to a kinetic energy of 150 Giga-electron-Volts (GeV). That’s equivalent to the kinetic energy of a mosquito moving at about 0.003 meters per second. But, protons are tiny and a little bit of energy goes a long way. In fact, 150 GeV takes a proton to more than 99% of the speed of light. To reach these high energies, the protons are accelerated in an enormous ring that is more than 3 km in circumference. However, as you can see from *Figure 1*, this immobile machine is not exactly easy or inexpensive to build at just any location!

Unfortunately, neutrino physics does not simply require a powerful particle accelerator—a large detector is also needed. For this reason, even the smallest neutrino detectors in the world are enormous. The MiniBooNE detector, which has “mini” in its name for a reason, is more than four stories high. Currently, “large” detectors are 22 stories high and just as wide. Envisioned future ultra-large detectors may be as tall as 100 m. Yet despite their enormous size, the detectors are instrumented to be extremely sensitive to very low energy interactions. Events caused by neutrinos from the Sun, which have 20,000 times less energy than the protons in the Main Injector accelerator, can be observed in these state-of-the-art detectors. However, when you are looking for low-energy interactions like these, you must build your detector deep underground. This is because there is a constant rain of particles, called cosmic rays, hitting the earth, some of which can mimic a



neutrino event. To hide from this neutrino background rain, the large detectors are built in mines or under mountains. This is a problem if you would like to make use of an accelerator-produced beam close to your detector. Fermilab, for example, is in the prairie, just outside Chicago, quite far from any mines or mountains.

Smaller and smarter

To paraphrase the proverb, “if the mountain won’t come to the accelerator then the accelerator must go to the mountain (or the mine),” the way to solve this problem is to develop smaller accelerators, which can be built inexpensively and placed close to a planned or existing large detector. Small accelerators can never reach the high energy of the accelerators like the Main Injector. However, what actually matters in producing neutrinos is (NUMBER OF PROTONS) x (ENERGY) / (SECOND); in other words: power. The energy can be low if the number of protons is high. What we are developing here at MIT are small accelerators that can match the Main Injector power because, despite being much lower energy, they can accelerate over a million times more protons per year.

A cyclotron accelerator works via principles that students learn in MIT’s 8.02 electricity and magnetism course (*Figure 2*).

Charged particles are injected at low energy into the center of the cyclotron. The magnetic field of the cyclotron causes these slow moving particles to bend and begin to orbit. Energy is added through radiofrequency (RF) waves, pushing the particles to higher and higher velocities, in an analogy to surfing. As the velocity grows, the charged particles follow larger and larger loops in the magnetic field. Eventually, the beam reaches the edge of the cyclotron and is directed onto a target, where the neutrinos are produced.

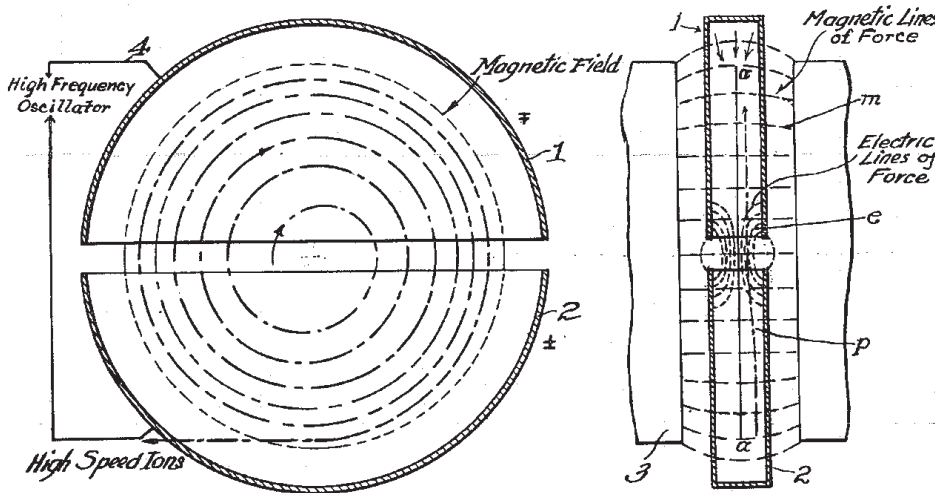


FIGURE 2

Lawrence's original patent for the first cyclotron, 1934, illustrating how a cyclotron works. Charge is injected at the center and then follows the spiral path, accelerating to high energy and exiting the machine.

Three, four...or more?

Neutrinos have presented the first and only clear observation of new physics beyond the Standard Model of particle physics to date, in the form of an effect called neutrino oscillations, where neutrinos

morph from one “flavor” to another. This ability to shape-shift deals a direct blow to the Standard Model, our best description of particle physics, and a theory where neutrinos have no mass. Massless particles, like photons, must be traveling at the speed of light; and when you travel at the ultimate speed, time is frozen and nothing can change. The fact that neutrinos can morph means they have a sense of time, and therefore have a mass.

The simplest extension of the Standard Model consistent with the oscillation observations to date calls for three neutrino mass states, which are each mixtures of the three known neutrino flavors.

However, a number of experiments seem to hint that there are more oscillation frequencies beyond those which can be explained in this three-neutrino picture. A solution that might explain these anomalous data sets adds an extra neutrino to the theory.

This sterile or non-interacting neutrino allows for additional mass states that can lead to higher frequency oscillations. If oscillations are truly showing evidence of these new particles, that would be revolutionary, demanding a new model that is way beyond the Standard!

This all sounds simple, of course, since cyclotrons have been around since the 1930s. Many alumni will fondly remember the cyclotron in building 44 (the “J” building). So what’s the big deal? The issue is that those early cyclotrons produced only nanoAmps of protons. To produce the power that neutrino physicists need, our cyclotrons need to provide milliAmps—a level of current that can run an LED flashlight. That’s a lot of protons! The fundamental problem with this idea is that when all of the same-charge particles are deposited into the center of the cyclotron they repel one another. The protons simply do not stay in a tight bunch and therefore fail to catch the RF wave in unison. Like disoriented surfers, they crash out. To reduce this problem, our collaboration has invented a trick. Instead of injecting single protons, our machine will inject and accelerate H_2^+ , a molecule of two protons held together by a single electron. At the end, the single electron is removed and we get two protons for every positive charge we put in.

The first cyclotron we would like to build will only be 60 MeV, which is 2,500 times less kinetic energy than the Fermilab Main Injector. But at 5 milliAmps, running continuously, it will be a very powerful machine. We have developed a novel targeting system for this. The protons will impinge on a beryllium target to produce a flood of neutrons into a surrounding lithium-7 sleeve, producing lithium-8. When the lithium-8 β -decays, it produces a very pure and intense source of anti-neutrinos. With this system, which we call IsoDAR, since it is an “Isotope Decay-At-Rest” source, we can produce 20% of a mole of neutrinos!

Our proposed cyclotron is only about 4 m in diameter (roughly the size of a lunar lander). This means that the accelerator and target can be installed underground, in a mine, next to an existing large neutrino detector. This combination of neutrino source and underground detector will be the perfect place to search for a new flavor neutrino that does not interact through Standard Model forces. (See “Three, four...or more?” at left.) As a nice side note, while running underground, we can use the beam that is not used for making neutrinos to produce strontium-82. This is the mother isotope of rubidium-82, which is a much-sought-after isotope for medical imaging. As a result, industry collaborators such as Best Cyclotron Systems have joined our group, donating millions of dollars in equipment to our project. However, we don’t intend to stop with IsoDAR. This 60 MeV accelerator can act as an injector of beam for a larger cyclotron that can raise the energy of the protons up

to 800 MeV. This larger cyclotron will be about 12 m across and 12 m high. While this is large, it could easily fit within the MIT dome and is orders of magnitude smaller than the accelerators presently used to make neutrino beams (*Figure 1*). The neutrino beams made with this machine come from pions and muons that are produced when 800 MeV protons hit a carbon target. The resulting neutrino decay-at-rest beam is produced when the pions and muons stop and decay through the weak interaction to produce neutrinos. The long term goal for this larger project is to study CP violation in the neutrino sector. (See “*Who stole the antimatter?*” at right.) This is a never-before-seen distinction between the behavior of neutrinos and antineutrinos that may help explain why the early universe had a preference for matter over antimatter. This asymmetry, which is the reason why there is something, instead of nothing, in our world today, could only exist if matter and antimatter were fundamentally different. The amplitude of the difference between matter neutrinos and antimatter neutrinos is described by the symbol δ_{CP} . Hence, the name for our larger project, DAE δ ALUS, which stands for Decay At rest Experiment to measure δ_{CP} At a Laboratory for Underground Science. The experimental setup will include a set of cyclotrons at various distances, 1 km, 8 km and 20 km, from a single, ultra-large, future underground detector.

Quintessential MIT

This idea of using small accelerators for neutrino physics came out of a quintessential MIT experience. One afternoon, when I had far too much to do, and yet wanted to procrastinate, I made the spur-of-the-moment decision to do something completely different: attend a seminar in the nuclear science and engineering department. The seminar, it turned out, was on high power cyclotrons for use in nuclear non-proliferation. What I suddenly realized was that the speaker was describing the accelerator of a neutrino physicist’s dreams. It is this kind of serendipity that can only happen here at MIT. This is how the project was born.

Any project like this needs a collaboration, and for this one to succeed, it was clear we needed leadership from a very unusual type of person. We needed someone who has great experience with accelerators, especially cyclotrons; someone with experience working in underground laboratories; someone with the vision to connect together the latest technology developed by the medical cyclotron industry; someone who loves a challenge and wants to work with graduate students; someone interested in

Who stole the antimatter?

The single biggest mystery in the entire universe is: who stole all of the antimatter? In the early universe, when the particles were formed from an initial burst of energy, there was an equal amount of matter and antimatter. But shortly after the Big Bang, an imbalance must have occurred, because when the last matter-antimatter annihilations were finished, a tiny bit of matter that makes up our present universe survived.

A way to explain this is through CP violation. CP is a discrete symmetry of nature that transforms matter to antimatter (that’s the “C”), while inverting its spatial coordinates, like a mirror (that’s “P”). If nature were CP invariant, then nature would treat matter and antimatter alike. In fact, the electromagnetic and strong interactions are CP invariant. But it turns out that the weak interaction is not. A tiny level of CP violation, where matter decays differently than antimatter, has been observed in composite particles made of quarks. But the effect is too small to explain the level of matter left in our universe. There must be another source of CP violation.

This has led physicists to suspect that the asymmetry comes from neutrinos. If CP is violated, oscillations of neutrinos and antineutrinos would be different. An observation of this difference in the neutrino sector would help to explain the matter/antimatter imbalance we observe in our universe today. That is why CP violation in neutrinos is currently on physicists’ “Most Wanted” list.



FIGURE 3
Alumnus Jose Alonso (right) and MIT postdoc Matthew Toups inspecting a potential underground site for IsoDAR. [Courtesy of Mike Shaevitz]

learning a whole new field, neutrino physics; someone who is willing to invest creativity and time. The kind of person that you need is surely...an MIT alum! Enter: **Jose Alonso PhD '67** (Figure 3). Jose has a wealth of accelerator experience from the Bevatron and SuperHILAC at University of California, Berkeley, the Spallation Neutron Source at Oak Ridge, and participation in many projects involving medical applications of cyclotrons and synchrotrons. In 2010, as this project was getting started, Jose was just retiring from his second career as the director of the Sanford Underground Laboratory for particle physics. Not one to be bored, Jose joined our project. He is an indispensable member of our team, and even more remarkable, his time is a donation to MIT.

Jose has helped us to build an extraordinary international collaboration. This includes physicists from Italy, Switzerland and Japan, as well as many groups in the U.S. In fact, he is taking data in our beamline development project in Vancouver right now, as this article is being written. Jose, along with MIT students and postdocs, has worked with industry and international collaborators to build the test beamline. This work is supported by the National Science Foundation and

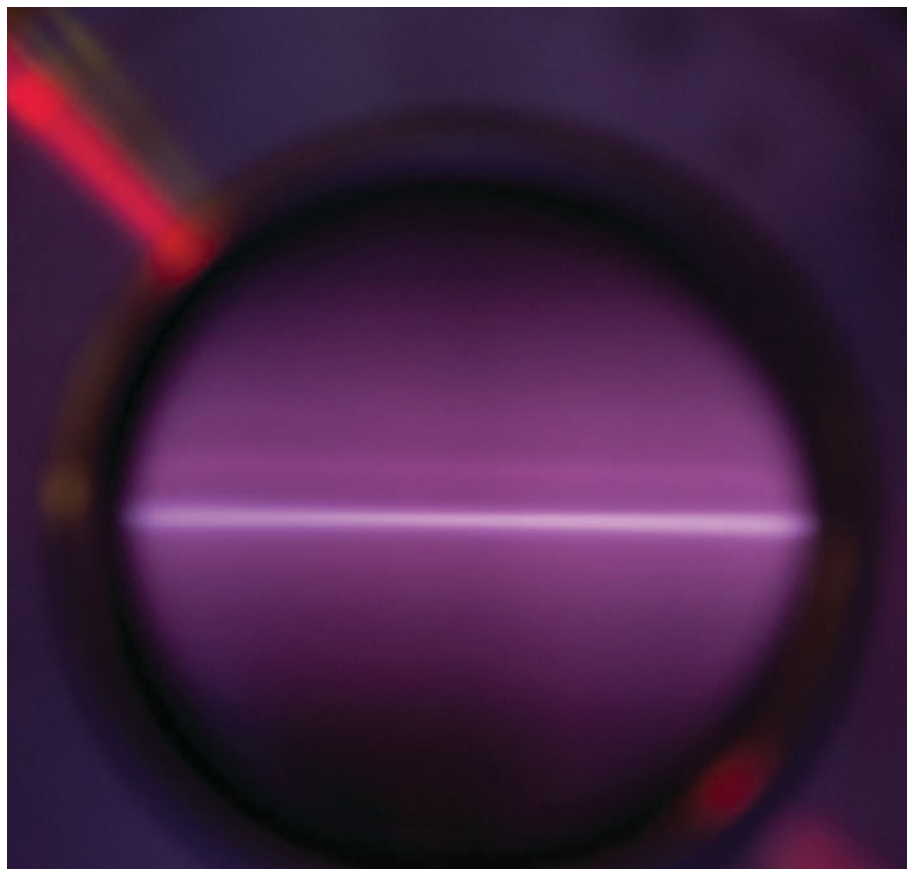


FIGURE 4
Our test beam, observed through a window in the beam line in Vancouver. [Courtesy of Jose Alonso]

MIT's Amar G. Bose Fund. We are testing the process of bringing the beam into the center of a cyclotron and letting the H_2^+ "catch the wave." Success in high intensity injection will represent the first big milestone in building these accelerators.

While we have many diagnostic tools for the beamline, sometimes it is just easiest if you can look in a window and see the beam. To make the beam visible, we bleed a tiny amount of air into the vacuum of the line, and the milliAmps of charged particles traversing the line cause the air to glow. The photo in *Figure 4* shows our beam through a small window in the beamline. While this tells us a lot about the beam's trajectory, it is also simply beautiful to look at. As my eight-year-old next-door neighbor (who intends to come to MIT) said, when she saw the picture of our beam, "it looks like what comes out of Hermione's wand!" Let's hope that this beam can be the powerful magic needed by the neutrino community to achieve our goals.

Neutrinos are the new frontier of particle physics. Understanding what they are and how they behave is a crucial next step in improving our understanding of the universe from the Big Bang to the present day. MIT's IsoDAR and DAE δ ALUS projects are leading the way forward in developing small, bright accelerators to answer these big questions. At the same time, the accelerators developed for this work have practical applications, too—something to think about the next time you wonder what all of these neutrinos zipping around have done for you and MIT lately.

JANET CONRAD, a professor of physics at MIT, leads a research group devoted to exploring the nature of the tiny, almost massless neutrino, which is sometimes called the "ghost particle."

Professor Conrad received her Bachelor of Science degree from Swarthmore College, her master's from Oxford University, and in 1993, her PhD from Harvard University. Before moving to a professorship at MIT, she was previously a postdoc, and then professor, at Columbia University.

Along with teaching at MIT, Prof. Conrad is involved in the MiniBooNE and MicroBooNE experiments located at Fermilab, as well as the Double Chooz experiment, based in France. She is also co-spokesperson of the proposed IsoDAR and DAE δ ALUS experiments.