MURAJ
Minnesota Undergraduate Research & Academic Journal
z.umn.edu/MURAJ

MURAJ: In Focus – Ken Heller, High Energy Physics

By Thomas Richardson

As an experimental high-energy physicist, Professor Ken Heller's job is to challenge our notions of the universe. Ken has done just that at the University of Minnesota, working with Fermilab and dozens of other institutions in the United States and abroad. His work takes him to two frontiers: one is the subatomic, involving the miniscule particles that make up all matter, and the other is physics education research, exploring how best to teach the next generation of physicists. In this MURAJ: In Focus profile, Dr. Heller explains the open questions and his ongoing investigations into these fields of physics research.

Physics is a rather broad subject – this makes sense, considering it spans the subatomic level to the whole universe. The field of high energy physics, or particle physics, stands out because it strikes at the big questions: what is matter made out of out? What are the fundamental forces that govern our world? Why do we exist at all?

I am fascinated by questions like these, and that's why I became a physics major at the University of Minnesota (UMN) – soon to graduate and begin physics grad school. Trying to find some answers, I talked with high energy physicist Prof. Ken Heller at UMN (Fig. 1). For him, high energy physics is all about breaking apart the physics we have and finding something even better. "Part of my nihilistic attitude towards some things is that I find great joy in destroying theories," he says. "That's what high energy experiment is all about."

In Ken's words, "high energy physics is specifically targeted to find the new structure of physics that we don't know about yet." He has been a part of several international collaborations to that end: including NOvA (NuMI Off-axis ν_e Appearance) and Mu2e (muon to electron) – two experiments that study physics beyond our standard model. Another focus of Ken's career is the physics education research group at UMN, which seeks to develop a new structure for university physics teaching.

Figure 1: Professor Ken Heller, experimental high energy physicist at the University of Minnesota.[1]

Let us start with a little background on high energy physics. This field investigates the subatomic elementary particles that make up our universe. By studying and modelling these particles – their properties, how they interact, and what they can decay into – physicists have created an incredibly successful theory called the standard model of particle physics[2]. The theory was given its modern form in 1973. Undergraduate physicists learn the basics of the standard model: for instance, that a proton is made out of 2 up quarks and 1 down quark held together by gluons. For the past 40 years, the standard model has been the bedrock of modern physics.

That being said, there are good reasons to be suspicious of the current framework of physics. As successful as it is, the standard model cannot explain some of the most important open questions in physics. Phenomena like dark matter, dark energy, and neutrino oscillations all fall outside the purview of the standard model. According to Ken, "we know that this wonderful theory we have is just not going to make it."

So how does one go about finding a better theory? Ken explains, "the tools are very varied. Of course, we use high energy accelerators – I like to make the analogy of the piñata approach. When in doubt, just smash it with a bigger hammer and see what comes out." By smashing particles together at high energies, physicists can observe different particles flying out of the collision. This is the method used in the Large Hadron Collider (LHC) at the European Organization for Nuclear Research (CERN) near Geneva, Switzerland. The LHC is probably the most famous example of high energy physics in action, and the project had help from the UMN Compact Muon Solenoid (CMS) group led by Professors Jeremy Mans, Roger Rusack, and Nadja Strobbe.

But that is not the only way of probing for new particles – another is to measure things very precisely and look for discrepancies between measurement and theory. Physicists can also look for events forbidden by the standard model. Evidence for either would indicate flaws in the standard model, hinting at new particles waiting to be discovered.

"So those are the three general sets of exploration strategies. Within each of them, we use detectors to detect particles – and any detector is fair game." At its most basic, a detector is just a device that tells you when a particle hits it (or passes through it) – so a catcher's mitt is a good detector for baseballs. High energy physicists might use quantum detectors, low-temperature detectors, high-temperature detectors, silicon detectors, gaseous detectors, very small detectors, very big detectors, and anything in between. Ken says, "one of the things I like about high energy physics is its variety. Everything is on the table."

Ken is currently working on Mu2e[3], an experiment that's an international collaboration between UMN, Fermilab (the US Department of Energy's particle physics laboratory in Illinois), and a host of other institutions. The experiment's history can be traced back to similar attempts by Russian physicists in the 1990's. The project has a seemingly simple goal: Ken says, "it's looking for something that's not supposed to happen: a muon which converts directly into an electron, without any other particles."

Muons (with symbol μ) are particles that are the same charge as electrons (e) but are about 200 times heavier. According to the standard model, a muon can decay into an electron plus two neutrinos (chargeless particles with symbol ν). This decay can be written as $\mu \rightarrow e + 2\nu$. But researchers working on Mu2e hope to observe a direct muon to electron decay ($\mu \rightarrow e$), which is forbidden by the standard model.

So why bother looking for $\mu \rightarrow e$? As Ken explains, “there are many theories that predict this to happen, theories beyond the standard model. Things like supersymmetric particles, or a new substructure of elementary particles.” Said theories have been around since the standard model itself was created (supersymmetry, or SUSY, was developed in 1977). If researchers working on Mu2e can confirm the $\mu \rightarrow e$ decay, we can learn a lot more about what physics beyond the standard model will look like.

It is by no means easy: according to some theories, the forbidden $\mu \rightarrow e$ decay is expected at a level of one part in 10^{16}, compared to the $\mu \rightarrow e + 2\nu$ decay. “It’s like looking for a grain of sand in a sand dune the size of Mt. Everest,” Ken says. “This is a very difficult experiment. It’s a collaboration of about 40 different institutions, both labs and other universities, from four countries.”

Figure 2: Researchers carefully construct a Mu2e detector module. Center is UMN post-doc Dan Ambrose. Undergraduates at UMN are helping to build 250 of these detectors.[4]

At UMN, there are 2 post docs, 3 graduate students, 5 graduated UMN undergrads, and 50 undergrads contributing to this search. Ken says, “what we’re doing here is we’re building the detector that measures the actual result of the experiment.” It is a difficult manufacturing process since the detector involves 250 modules with 22,000 detecting tubes (Fig. 2) – and quality control must be perfect. If all goes well, Mu2e will run in 2024.

Meanwhile, Ken together with UMN Professors Greg Pawloski and Marvin Marshak are still taking data with NOvA (NuMI Off-axis ν_e Appearance), an experiment that measures neutrino oscillations[5]. The NOvA project is an even bigger collaboration, involving over 260 scientists from 49 institutions and 8 countries. It started taking data in 2014, using a large particle detector in Minnesota built by 700 UMN undergrads over 4 years (Fig. 3).

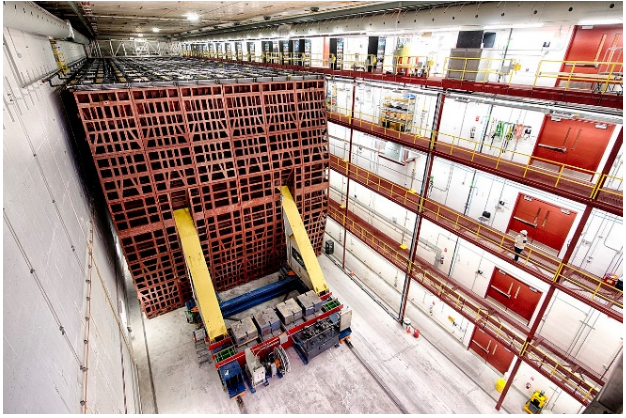

Figure 3: NOvA’s 4-storey neutrino detector. NOvA researchers fire a beam of neutrinos from Fermilab, IL, through 810 km of solid Earth, to this detector located in Ash River, MN. The long distance allows neutrinos to oscillate between flavor states.[6]

Neutrinos are chargeless particles that have a very small mass (factor of 10^6 smaller than electron mass). This makes them ‘ghost’ particles, as they interact very weakly with matter – in fact, trillions pass straight through the Earth every second. Neutrinos come in three 'flavor' states: the electron neutrino, muon neutrino, and tau neutrino.

For a long time in particle physics, neutrinos were viewed as very simple massless particles, as predicted by the standard model. But not only do neutrinos have mass – each of the three flavors that we observe is a mixture of three neutrino mass states (and vice versa). The mixture changes with time, so that the identity of a neutrino oscillates between mass states. It's an example of quantum mechanics in action.

Neutrino oscillations were discovered in the 1960's by the Brookhaven Solar Neutrino Experiment, and confirmed in the 1990's by the Super-Kamiokande experiment in Japan and the Sudbury Neutrino Observatory in Canada. Ken says, "Experiments were seeing anomalies, and it took some time to actually put the experiments together to nail down the fact that neutrinos did oscillate, therefore neutrinos had mass. That was a discovery of physics beyond the standard model."

But there is still much we do not know about these oscillations. NOvA has two main goals: "one is to determine the mass hierarchy of neutrinos," Ken says. "We know the differences in masses, but we don't know what order they're in. Knowing the mass hierarchy can help us understand why particles have the masses they have."

These findings could deal with more than just neutrinos. Ken continues, "the other big question is even bigger: why does the universe exist?" This question deals with antimatter (not to be confused with dark matter). Each particle has an antiparticle, which behaves in much the same way (for example, antielectrons and antiprotons can combine to make antihydrogen). But if matter and antimatter ever touch, they annihilate each other in extremely energetic explosions of gamma radiation.

According to the standard model, the energy produced by the Big Bang should have made matter and antimatter in equal amounts. "Everywhere we look, in stars or galaxies, it's all matter," Ken says. "The question is, where did the antimatter go?" The answer may lie in neutrino and antineutrino oscillations if these processes slightly favor the production of matter over antimatter.

Beyond those questions, researchers at Fermilab also use NOvA's neutrino detectors to keep a lookout for interesting phenomena in our universe like magnetic monopoles, weird cosmic rays, and supernovae in our galaxy.

But Ken's research is not all particles. He says, "it's much harder to do, but I'm interested in how people learn. In particular, how people learn physics." Along with Prof. Patricia Heller, Ken helped form the physics education research group at UMN, one of the first in the country.

The group has done a lot of research on problem-solving and how to best teach important problem-solving skills. Currently, the group works on computer-assisted physics education using intelligent digital tutors. Ken explains, "a computer has infinite patience and can work with you in the way you want to work, at the time you want to work, and for the amount of time you want to work."

The group is also trying to identify some of the diversity barriers to physics. Ken says, "we know there's something beyond our 'standard model' of teaching because we can just look at our own field. Physics is one of the least diverse professions there is. That tells you right away that something is wrong with the way that we bring people into physics."

The group looks at the implicit requirements that introductory classes have for students – those beyond simply knowing the physics. This includes performance in standardized tests or the ability to engage with lecture-style class formats (this can be more difficult for visual or kinesthetic learners). Ken argues that a lot of those requirements may be unnecessary and might act as filters to certain populations, reducing diversity in physics. Ken says, "you have to think outside of your paradigms, just like in high energy. You realize that we could do so much better."

With any luck, we could soon see those old theories supplanted – for both particles and people. For particle physics, that could mean a revolutionary theory of fundamental physics: in the past, these leaps have led to great advances in technology (e.g. how quantum physics led to modern electronics). For physics education, we might see more effective teaching styles in the classroom, computerized tutors making physics more accessible to larger numbers of students, and hopefully a much more diverse population of physicists.

Though we cannot be sure what comes next, all of this research indicates that physics is overdue for an overhaul. Ken explains, "it's a great time to be in physics because we're on one of those cusps where you know that your physics is wrong. You know because of anomalies and things you don't understand. You just don't know what direction to go. We're looking for that breakthrough."

[1] Figure taken from UMN CSE webpage at cse.umn.edu/college/feature-stories/head-class.

[2] For an overview on the standard model, see home.cern/science/physics/standard-model.

[3] For more info about Mu2e, see mu2e.fnal.gov.

[4] Figure taken from Fermilab webpage at vms.fnal.gov/asset/detail?recid=1933764&recid=1933764

[5] For more info about NOvA, see novaexperiment.fnal.gov.

[6] Figure taken from Fermilab webpage at novaexperiment.fnal.gov.

This profile is part of the series MURAJ: In Focus, *organized by the Minnesota Undergraduate Research & Academic Journal, with funding from the University of Minnesota Office of Undergraduate Education.*

Thomas Richardson is a graduating senior in the physics major at the University of Minnesota. His research interests are atomic & condensed matter physics. He is a reviewer *for the Minnesota Undergraduate Research & Academic Journal.*

Dr. Kenneth Heller is a professor of physics in the School of Physics and Astronomy at the University of Minnesota. His research interests include experimental high energy physics, particularly physics beyond the standard model, & physics education research relating.