DEAP-3600: It's pretty deep!

As a geology student interested in physics, I've had the incredible opportunity this past summer to work as a research assistant on an experiment at SNOLAB. For those who aren't familiar, SNOLAB is a Canadian physics laboratory specializing in neutrino and dark matter physics. They are the world's deepest operational clean room facility, located at a depth of 2070 m (6800 ft) near Sudbury, Ontario! The extreme depth of this lab is very important, as it is the overlying rock that provides shielding from cosmic rays to allow for the study of very rare interactions and weak processes. Though it is a Canadian facility, SNOLAB hosts experiments that are run by scientists from around the globe. One of these experiments is a dark matter detector called DEAP-3600 (Dark Matter Experiment using Argon Pulse-shape Discrimination) and I will be talking about how we've been using this detector to study the relationship between cosmic muons and atmospheric temperature.

What are cosmic rays, and where do they come from?

It may be interesting to learn that cosmic rays are, in fact, not even rays! At the time of their discovery 100 years ago, scientists thought they were a form of electromagnetic radiation (aka light) which is why they were called "rays". Since then we've learned that cosmic rays are actually made up of an assortment of high-energy particles travelling through space at nearly the speed of light, and that they come from a variety of locations both within our galaxy (the sun, supernovas) and beyond. The vast majority of these particles are protons, but we also find that cosmic rays are made of other sub-atomic particles including electrons, neutrons, and neutrinos. Since protons and electrons are charged (positive and negative, respectively), cosmic rays can be deflected by the magnetic fields of stars and planets as they travel through our galaxy and solar system. The result is that their paths have been scrambled to the point where we can no longer trace back exactly where they originated, complicating studies on how they are formed. A lot of cosmic ray physics is still a mystery!

Onto the formation of muons…

When high-energy primary cosmic rays do eventually reach the Earth, they collide with particles in our atmosphere (e.g. oxygen and nitrogen molecules) and shatter their nuclei in a process called spallation. This results in a hadronic shower, or an air shower, which is a cascade of ionized particles and electromagnetic radiation in the direction of the original cosmic ray. An important product of this process is the muon ("MYOO-on"), a sub-atomic particle that is similar to an electron but is about 200 times heavier. Muons are extremely penetrating and, if they start with enough energy, they are able to punch through the two kilometres of rock separating the surface from DEAP-3600! At sea level, they arrive at a rate near one muon per square centimeter per minute, but this rate is significantly reduced if you increase the density or volume of material that the muons have to pass through. In short, only the high-energy muons are able to make it underground to our detector, and the production of high- vs low-energy muons is affected by atmospheric temperature. Delving into more detail, muons are formed specifically by the decay of kaons ("KAY-ons") and pions ('PIE-ons"), some common secondary particles that are formed at the beginning of a hadronic shower. In the brief window of time in which kaons and pions exist, they can either decay into high-energy muons or interact with air molecules to produce lower-energy cascades where lower-energy muons are eventually produced. When air temperature increases, the density of the air decreases, which means air molecules are more spread apart. As such, the probability that kaons and pions will interact with air molecules and ultimately form low-energy muons is reduced. These interactions and decays occur high in the atmosphere in a region called the stratosphere, spanning altitudes of 10 – 50 km. Since stratosphere temperatures are largely constant, usually changing on the time scale of seasons, we can expect more high-energy muons to be produced in the summer than the winter.

What do we do with this?

Okay, cosmic rays from outer space collide with particles in our atmosphere and produce muons. Now what? As mentioned earlier, muons travelling with enough energy can penetrate deep into the earth. However, they lose energy in a process called attenuation as they pass through dense materials like rock. The denser the material, the faster energy is lost; this is where the extreme depth of SNOLAB is an asset. Since the main goal of DEAP-3600 is to detect extremely rare particles of dark matter, it is important to block out all other signals. The two kilometres of overburden protecting the detector ensures that only muons starting with very high energies can make it to the detector. The implication of accounting for its temperature dependence is that we would expect to see more muons during the summer than the winter. But how does the detector actually “see” these muons? In its simplest form, DEAP-3600 is a plastic sphere contained in a large can of water. The plastic sphere contains 3300 kg of liquid argon that scintillates, producing light, when high-energy particles interact with it. The faint light is captured by 255 specialized cameras, called photomultiplier tubes (PMTs), and analyzed to determine characteristics of the particle that was just observed. There are also 48 of these cameras pointed away from the liquid argon and out towards the surrounding water, where most of the muons are observed. We are used to thinking that nothing can travel faster than the speed of light, however this is only true in a vacuum; light slows down when it passes through other materials like water. A special kind of light called Cherenkov radiation is emitted when charged particles travel faster than the speed of light in that medium. Muons fly through the water tank at speeds above 255,000 kilometers per second, which is how fast light can propagate through water. The Cherenkov radiation produced by muons can be thought of as “sonic booms” of light, and this is the process that allows muons to be seen by the detector! By recording information on these flashes of light from the water tank and when they occurred, we are able to quantify the rate of muons reaching our detector and how this rate changes over time. An annual modulating signal in muon rate has been correlated with seasonal changes in temperature and observed by other detectors in Italy, France, and the USA. This is a measurement we hope to repeat with DEAP-3600. Studying and characterizing the muon signal is something that benefits our dark matter search by gaining a better understanding of the various backgrounds that exist. It also provides insight into atmospheric physics, galactic physics, and has applications in fields like muon tomography and space weather monitoring.

I would like to acknowledge the Arthur B. McDonald Canadian Astroparticle Physics Research Institute for facilitating this internship experience.

Emily Darling, August 2020