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Introduction

I worked for Dr. Tripathi in the High Energy Physics Group at UC Davis this summer. I worked on two unrelated projects, so this paper deals with them in two unrelated sections. Both projects were intended to search for the dark matter particle. The first was LUX, the large underground xenon experiment, which looked for the signature photons emitted by a nuclear recoil in a heavily shielded, extremely low background tank. The second was the CACTUS gamma ray telescope, which looked for gamma rays emitted by the Draco cluster, a neighbor to our own galaxy that is 95 percent dark matter.

Electronics

For the LUX dark matter experiment, I worked on designing and manufacturing electronics. That entailed learning the PADS circuit design and layout software. There are two principal programs: one for making schematics and one for making circuit board layouts and production files. It also entailed learning a lot about the theory of circuit board design, finding and ordering parts, and working with the vendor that would eventually manufacture the board. I was greatly assisted by the department engineer Britt Holbrook, who oversaw my designs at every stage. I accomplished three things for this project this summer: I created a preliminary schematic for a PMT base circuit, a schematics for a PMT pickoff circuit, and a layout and gerber files for an 8-channel pickoff board.

PMT stands for PhotoMultiplier Tube, which is a device that emits an electrical pulse when it is hit by a photon. They are used in a lot of dark matter experiments, where often a photon is a sign that a dark matter interaction has occurred. A PMT has a photocathode at one end, which is a piece of a material that ejects an electron when struck by a photon. They usually have a range of wavelengths at which they are most sensitive, though the quantum efficiency (the probability of ejecting an electron if struck by a photon) is less than 30% even at the most sensitive wavelengths. The resulting electron is accelerated by a potential until it strikes a dynode, which emits 3-4 electrons for each electron that strikes it. Those new electrons are accelerated to the next dynode by another potential difference, and so on through the rest of the plates (ten, in the model used in LUX). The end result is a large shower of electrons striking the anode, creating a electrical pulse that is about 10 ns wide.

In order to operate, the PMT needs to be provided with potential differences between each dynode. The PMT base circuit is supposed to take about 2000 volts of DC voltage and separate it so that successive dynode receives a few hundred volts less than its predecessor. It is essentially a voltage divider times 10, plus some capacitors in parallel to damp out effects from the pulse on the last few dynodes. Before the last few dynodes, the pulse is so small that it would have negligible effects.

The standard design for a base circuit assumes that there is only one input/output point to the circuit. The high voltage needs to be supplied at that point, and the high frequency signal pulse will be there as well. Generally speaking, the cable coming out of the base of the PMT is connected to a box called a pickoff box, which contains a pickoff circuit that separates the signal pulse from the DC power and sends it to the amplifiers and other electronics. The pickoff circuit is fairly simple theoretically. A cable coming from the high voltage supply passes through a low-pass filter and then connects to the PMT cable. The PMT cable is also connected to the cable to the front-end electronics through a high-pass filter.
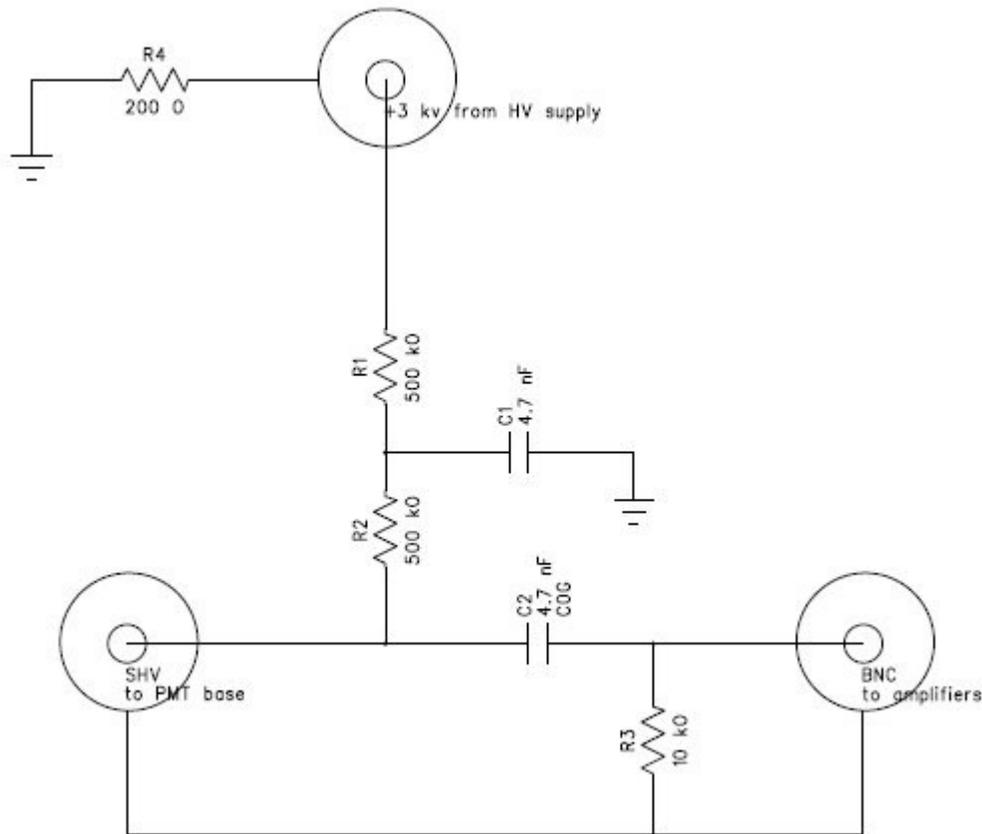

Fig. 1: simplified schematic for a pickoff circuit.

My first project for the summer was to create a schematic for a circuit that combined the base circuit with the pickoff box circuits. This combined circuit will be used to design custom bases for the PMTs inside the LUX cryostat, that will have signal out and DC supply in on two separate cables attached to the base.

I also created a detailed schematic for a pickoff circuit that I used as the basis for a circuit board design. The design called for a high-capacitance (4.7 nF) capacitor than was rated to withstand 2 kV of DC, and was made of a special dielectric that had a special high-frequency response. We would have had to order directly from the manufacturer in Britain,

which would have taken at least two months. Instead, we decided to use a smaller capacitor and put it in parallel with a 4.7 nF capacitor made of a more common dielectric. We inserted small resistor between the two capacitors to reduce resonance effects. The result was the picture below.

Fig. 2. Actual schematic for a pickoff circuit.

At the end of the summer, while waiting for Britt and the contractor to finalize the design, I worked with graduate student John Felde to make a boardless prototype, mostly to test whether this substitution would introduce any distortion into the circuit. We had some difficulties finding a cable to connect the pulse generator to the pickoff box, and our workaround caused some distortion in the signal, but we didn't see anything unexpected. Even better, we tested the box with a small PMT, and found that it performed fairly well. The pulse was slightly stretched, 50 ns vs. 10 ns, but still reasonable fast. There was about a 10 to 15% reflection from the connection between the PMT and the box, but that should be eliminated be using an actual board. With a printed circuit point, we took care to make sure that the impedance of the connections from the PMT in to the signal out was 50 ohms.

The circuit board design I created in PADS was for an eight-channel board, meaning that each board contained 8 pickoff circuits. One side had most of the components, and the other side mostly consisted of the ground plane. The greatest challenge was designing the interface between the SHV connectors and the board. We wanted to use single-pin connectors, so, in order to prevent rotation, we needed to mill D-shaped holes in the board rather than drill a circular hole. Then we needed to plate the hole and, for the input from the HV supply, connect it to a 200 ohm resistor to ground. PADS generally lets you design parts and define pads, where you can define drill holes and plating around them, or just plating. All connections are made from pads. PADS does not have a way to define a milled hole instead of a drilled hole in a pad. It took two weeks, but in discovered that the best workaround was to draw a milled hole, with two carefully drawn copper cutouts around it, one on the top and one on the bottom. The design and associated files was sent off to the contractor, who had not finished making changes to it before I left.

C.A.C.T.U.S. simulations

The Air Cherenkov Telescope at Solar Two (C.A.C.T.U.S.) ran from Fall 2004 to fall 2005. It observed the Draco cluster, a neighbor to our own galaxy that is composed of 95% dark matter, looking for gamma-ray emissions. One candidate for the dark matter particle, the neutralino, a particle predicted by supersymmetry, is its own anti-particle. So one would expect high-energy annihilations to occur in any large cluster of dark matter, which could transmit over long distances as high-energy gamma rays. When gamma rays enter the earth's atmosphere, they interact with the nuclei in air to produce pairs of electrons and positrons. These particles are quickly captured by nearby atoms, and as they slow down from close to c to close to zero, they shed the energy in new gamma rays, which in turn produce new pairs of particles. The result is a shower of relativistic electron and positron pairs from an incident gamma ray. These particles are moving so fast that they are faster than the speed of light in air, and thus emit Cherenkov radiation – the light equivalent of a sonic boom. The spectrum of Cherenkov radiation includes visible spectrum light, which can pass without interference through the earth's atmosphere. At night, through this process, there are constant extremely bright pulses of Cherenkov light that one could see from the ground—if they lasted more than tens of nanoseconds.

The CACTUS telescope records these flashes with an array of mirrors and PMTs. UC Davis researchers use a chain of simulations to understand exactly how their detector will capture evidence of gamma rays. The first simulation, Cascade, models the generation of a particle shower from a gamma ray. The next, Cherenk, models the generation of Cherenkov light by these particles. Then a program called s2optics advances the Cherenkov photons through the optical array of CACTUS, and sends the photons that successfully hit PMTs to s2elec, which models the electrical systems of CACTUS.

My project was to test and set up a new simulation program, Corsika. Corsika generates the particle shower from the interaction of cosmic ray particles and gamma rays with the earth's upper atmosphere, and can also model the Cherenkov light produced by the shower.

In terms of the old simulation chain, it would replace Caskade and Cherenk, producing photons that would then be the input for s2optics.

The first step was installing Corsika. The standard Corsika Cherenkov output option did not suit our purposes, because it was set up to track photons in bunches and didn't report their energy. Also, the output did not seem to match its description in the Corsika user's manual. Instead, we used an option to give the photons in a binary COR------ file, giving the x and y positions, normalized x and y direction vectors, wavelength, and relative time of arrival. This had been designed for the Stacee experiment, and it was poorly documented. By visiting the webpage of the original researcher, I was able to find code for a C++ class called CorsikaStacee for reading the binary output. I edited it so that it could recognize and read event headers in the middle of the file. I also wrote several programs implementing the CorsikaStacee class, the most useful of which read through a COR file, and printed out the number, energy, and number of photons produced for each event.

The next step was to compare Corsika with Caskade+Cherenk before s2optics. We set up two test runs with each simulation. The parameters were 2000 events with energies between 50 to 500 GeV, and 500 with energies between 500 and 1000, all showers pointed straight down. Using the photon counter described earlier, and an analogue I wrote for Cherenk, I generated a table that I then graphed using the ROOT analysis program. The result was a clear linear relationship between event energy and number of photons for both programs, but Corsika generated roughly 2 and a half times as many photons per unit of energy of the generating photon.
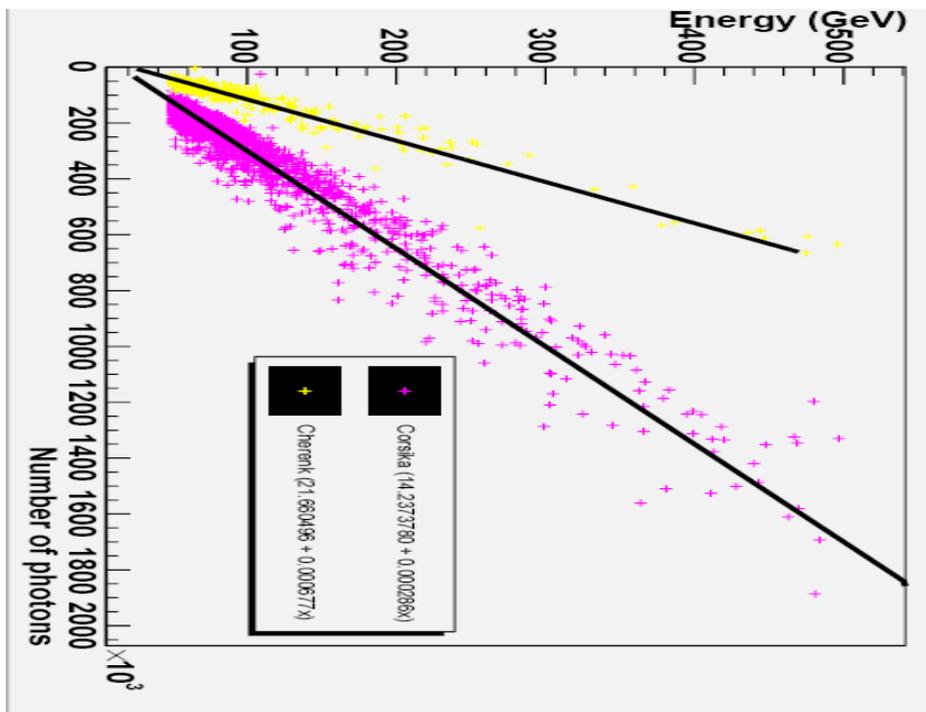

Fig. 3. Comparison of number of photons generated by Corsika and Caskade+Cherenk.

After that, we decided to prioritize doing simulations with Corsika. We started doing runs simulating data from the Crab cluster on the CMS cluster. However, we stalled for a bit trying to run the results through s2optics, because I needed to debug the newly created Corsika interface (created by Peter Marleau, who was on vacation at this point) in s2optics. It wasn't until the very end of the REU program that I had finished debugging and had Corsika set up to run simulations and pipe the output to s2optics. UCD undergrad Branden Sievers will be taking over and actually running the necessary simulations in Corsika.