Comparing the Calibration and Simulation Data of the Cryogenic Dark Matter Search

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August 9, 2010

Prepared in partial fulfillment of the requirements of the Office of Science, Department of Energy’s Science Undergraduate Laboratory Internship under the direction of Rudy Resch at the Kavli Institute for Particle Astrophysics and Cosmology, Stanford Linear Accelerator Center.

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ABSTRACT

Comparing the Calibration and Simulation Data of the Cryogenic Dark Matter Search. ANTHONY DIFRANZO (Rensselaer Polytechnic Institute, Troy, NY 12180) RUDY RESCH (Kavli Institute for Particle Astrophysics and Cosmology, Stanford Linear Accelerator Center, Stanford, CA 94025)

The Cryogenic Dark Matter Search collaboration is preparing a new experiment called SuperCDMS. Germanium detectors will be used to study a scattering event with dark matter by measuring the ionization and heat produced during such an event. To prepare for the experiment the detectors are being calibrated with varying radioactive sources. This calibration is also being modeled by a Monte Carlo simulation; this includes modeling everything from the radiation production to the raw data collected by the detector. The calibration data will be used to validate the results of the detector simulation. This research will focus on the information given by the heat, or phonons, released during an event. More specifically, this research will look only at events that occur very close to the detector surface. From the raw output of the data and simulation three parameters will be determined: the rise time, the decay time, and time to position independence. It was found that the simulation’s risetime and time to position independence was generally smaller than that of the data. However, the decay time was found to be larger in the simulation than what was measured. These differences show that the simulation is not yet complete. The difference in risetime implies that the phonons are not spread out enough when they reach the detector walls, a look at the Luke phonon and charge transport could improve this. The long decay time in the simulation implies that the rate phonons are being absorbed is underestimated. Finally, the small time to position independence in the simulation could be due to a low absorption of phonons into the sensors. A simple solution may be to alter the parameters that control the simulation, while still remaining in physically sensible, to help match simulation and data.
INTRODUCTION

In 1959, Louise Volders discovered that the rotation curve of the spiral galaxy M33 doesn’t match the predictions given by Newtonian Dynamics. Instead of the velocities dropping off like the inverse of the square root of the distance, they are nearly constant. The two main hypotheses that resulted to explain this were the Modified Newtonian Dynamics, or MOND, and Dark Matter. MOND assumes that Newtonian Dynamics is incorrect. While the Dark Matter hypothesis says that there is invisible matter that is altering the gravitational field of a galaxy. Both hypotheses are able to explain the spiral galaxy phenomenon.

In 2006, a study was carried out on the Gravitational Lensing due to the Bullet Cluster, which consists of two galaxy clusters colliding. The study found that the center of the gravitational potential of the galaxy was not located with that predicted by the visible matter alone. Further research showed that the collision separated the dark matter from the visible matter. Since MOND is not able to explain this, the Bullet Cluster has become a major piece of evidence in support of dark matter. The visible matter, such as interstellar gas is mapped using x-rays. While all the mass is mapped using gravitational lensing techniques. The comparison shows that there must be extra mass, in fact Dark Matter appears to be clustered in halos around galaxies. With the compelling amount of evidence, most physicists have accepted Dark Matter as the most viable hypothesis.

Assuming Dark Matter exists, the first question is what is Dark Matter made of? It doesn’t interact via the electromagnetic force, since we are not able to probe it with light. Dark Matter appears to be nearly non-interacting and predominantly non-relativistic, often referred to as cold. Of the many candidates, Weakly Interacting Massive Particles or WIMPs are the most prominent. A WIMP is a hypothetical class of particles which include the neutralino, Kaluza-Klein particle, and branon. They are believed to interact only through the weak force and gravity. The discovery of neutralinos would be particularly exciting as it would give credibility to the Supersymmetric model[1].
Now the hypothesis must be tested; how will WIMPs be detected? WIMPs, like neutrinos, in a collider must be found through the missing energy and momentum of a collision, as WIMPs will not interact well with detectors. The highest energies are currently attained with hadron, rather than lepton, colliders. Since hadrons are not elementary, the momenta of their constituents are not very well defined. Therefore, colliders will not be very useful. Indirect detection is also possible by looking for WIMP pair annihilation in space; however this is accompanied by large uncertainty. The third option is direct detection; this method looks for the elastic scattering of WIMPs with the nuclei of a particle detector[1].

The Cryogenic Dark Matter Search, or CDMS, is an experiment looking to directly observe these particles and hopefully determine their candidacy as constituents of Dark Matter. The experiment consists of germanium detectors, which must be held at millikelvin temperatures, to detect an interaction between a dark matter particle and a Ge nucleus. Since dark matter is believed to be spread throughout our galaxy and is slowly moving we can move the detectors through space to get collisions. As the Earth and our solar system move through the dark matter halo of the Milky Way Galaxy, the detectors will hopefully interact with a Dark Matter particle.

**MATERIALS AND METHODS**

The detector geometry used in this experiment is known as an Interleaved Z-sensitive Ionization and Phonon, or iZIP. The top and bottom of the Ge detectors have contacts to collect charge and phonons. These contacts are partitioned into regions, in order to gain information about the location of an interaction. Sensitivity to both the distribution and timing of phonon collection between each region determines where in the detector the event occurred. The phonon channels allow us to determine the amount of energy in an interaction. The charge and phonon channel together are used to distinguish between nuclear and electron recoil, which is crucial in discriminating between signal and background. To further help with
discrimination, these detectors are housed underground to reduce events involving cosmic radiation.

Keeping the detectors at low temperatures has a dual purpose. First, a warm crystal lattice will naturally contain a high density of thermal phonons. Thermal phonons greatly increase the noise in the collected phonon data. However, this noise can be reduced by holding the detectors at millikelvin temperatures. Second, this low temperature is also required for our method of phonon detection. The phonon detection relies on Transition Edge Sensors, or TES, which need to be kept at a temperature where it can easily transition from a superconducting to normal state. The phonons are collected at the TES on the surface of the Ge. As phonons are absorbed, the TESs heat up, bringing the sensor out of its superconducting state[2]. This transition is accompanied by a sharp, measurable increase in the resistance of the sensor, which is recorded as part of our data collection.

There are three forms of phonons in our detector that we must study to properly analyze the data. The first are called Luke phonons, these are radiated from charged particles that move greater than the speed of sound within that medium. The second types are called intrinsic phonons. These are released during the interaction. They usually undergo anharmonic decay, where a phonon will split into two phonons with less energy. This process continues until a phonon can’t lose any more energy, in which case it is referred to as ballistic. The third are known as recombination phonons[1]. These are released when electrons and holes recombine, often through a defect states rather than a direct transition across the band gap, this is known as Shockley Reed Hall recombination. The defect state population is usually greater at the edges of a crystal lattice; therefore most recombination phonons are created at the surfaces of the detector.

Charge transportation will also be very important to modeling our detectors. A transverse electric field will be applied to the detector to draw electrons out one side and holes out the other. However, an important process to account for is oblique propagation. Here electrons will not travel in a straight line following the electric field. Instead, they will follow...
valleys” within the germanium, therefore taking a slightly longer path through the crystal. However, holes travel directly along the field lines.

The Monte Carlo simulation of the events will serve as a way for us to prove we understand the detector. There are four distinct levels to this simulation: source radiation, scattering, transport, and measurement. In this first step GEANT4 places the source near to one face of the detector, masks can be placed between the source and detector in the program to make a pattern of radiation on the surface. The incident particles are then allowed to scatter off of lattice sites in the Ge. GEANT4 simulates the positions and energies of these scattering events. In the third step, these positions and energies are used to determine the initial number and locations of the phonons. These phonon are allowed to move throughout the detector and undergo processes previously discussed. In the last step, these phonons must be collected. For simplicity the detector faces are broken into regions. The regions are assigned a probability of absorbing a phonon, this with the number of phonons incident on this regions determines how many are collected. The final result is a pulse that models the output of the actual detector during a calibration data run.

We must now have actual data on the detectors to which we will compare the simulation. The detectors are calibrated with radioactive sources such as Barium-133, Californium-252, and Cadmium-109. Each of these calibration sources provides a different type of event that we are interested in. Ba-133 radiation will produce electron recoil, Cf-252 radiation will produce nuclear recoil, and Cd-109 radiation will produce events that occur very close to the surface of our detector. This range of event types is necessary in distinguishing background from signal. I am specifically interested in surface events for this project, meaning Cd-109 will be used as the source for my data. This isotope of cadmium is a beta-particle emitter, meaning it radiates electrons and positrons. These beta particles are relatively low energy and will interact close to the surface of the detector. We also need to be sure that the simulation and data are actually measuring the same thing. We can help ensure this by applying quality cuts to our data. These cuts remove events that do not match what the
simulation is attempting to model. For example, we may be only looking at a certain energy range or perhaps we want to isolate surface events.

Both the data and simulation output a pulse. The raw pulse is actually the time dependent current through the TES. If the density of phonons at the surface of a TES is high then many phonons should be collected. This in turn will increase the current through the TES. Figure 1 shows an example of such a data pulse. When the pulse is increasing the density of phonons is increasing at the surface, likewise when it is decreasing the number of phonons must be decreasing. After some time phonons have diffused uniformly throughout the detector. At this point phonons must slowly leak out, this leads to a long decay tail in the pulse. The lower plot shows these same pulses but are all scaled so that the slow decay tails match up. Note that Figure 1 contains a diagram of the channel regions. One is located on the bottom and the other is located on the top of the detector. Also, note that the regions on top are orthogonal to the regions on the top. This gives us more information on the position of events.

The data and simulation pulses are compared against each other and analyzed. The preliminary analysis includes determining for each event the decay time, the rise time, the amount of energy deposited into each channel, etc. These parameters are then plotted in a histogram so data and simulation can be directly compared. The histograms are normalized so that all their areas are unity. Observing differences at this level serves as a gauge of how well we understand our detector and can help determine the most important input parameters for the simulation.

There are several outputs from the comparison program that are of particular importance; I will focus on three such outputs. The first is called the 10-40% Rise Time. This is the time between the points when the phonon pulse is 10 and 40% of its maximum height. This piece of data gives us information of phonon transportation, particularly the Luke phonons since they reach the detector surface first. This also serves to discriminate between event types. Surface events range in recoil energy and ionization energy, therefore they can easily
be misinterpreted as nuclear or electron recoil events. However, surface events are also accompanied by small rise times, while nuclear recoils tend to have large rise times.

The second is the decay time. This is the time it takes for the pulse to decay to a factor of e of its maximum height; this is a typical convention for any given exponential decay. The intrinsic phonons undergo down conversion and eventually become ballistic. In this mode they are unlikely to down convert and will travel more readily to a detector. Therefore, the phonon pulse will decay faster as more and more phonons enter the ballistic regime. The decay time then allows us to see how long it takes before phonons become ballistic and if the down conversion process is properly modeled. This also tells us if our absorption rate into the TES is correct.

The third is known as the time to position independence. This is the amount of time before we can no longer tell where an event occurred by looking at the pulses. In other words, at this time phonons have diffused uniformly throughout the detector. This again, will tell us if the phonon transport processes have been modeled properly. The lower plot in Figure 1 shows the scaled pulses, after a short time these pulses converge and position independence has been achieved.

The aforementioned simulation must account for many processes, including those related to transportation in the crystal. Other basic considerations comprise probability of phonon absorption into the TES and how much energy will be collected into each partition in the sensor. The main goal of this research is to construct a complete analysis and comparison between simulation and calibration data sets. I am mainly concerned with data sets involving Cd-109, which as previously stated produces surface events. Outside of comparison the simulation is also used to test different detector geometries before they are made. Though this method is not perfect it does allow us to exclude certain geometries before the trouble is gone through to fabricate the detectors.
RESULTS

The following are all based on phonon output from Cd-109 simulation and data runs. The 10-40% Rise Time Histogram is shown in Figure 2. The top plots the rise time for the fastest channel for each event, note that this may not be the same channel for every event. The bottom plots the slowest risetime for each event. The data is plotted in gray and the simulation in black dotted lines. The agreement is not spectacular between simulation and data; however, their ranges match up well. The fastest channel ranges from 0 to 12 µs and the slowest ranges from 35 to 80 µs, approximately.

The Decay Time histogram is shown in Figure 3. The differences are very apparent here, the data distribution is broader and it’s mean is smaller than that of simulation. The data appears to decay about 200 µs faster than the simulation. However, they do share the same functional form; both have very clean Gaussian distributions. Also, note the height difference between the two distributions.

The Time to Position Independence Histogram is shown in Figure 4. The simulation shows position independence being reached around 250 µs, while data shows it to most likely occur around 400 µs. Also, note that their functional forms match, they are both Gaussians skewed to the right.

DISCUSSION AND CONCLUSIONS

For both the fastest and slowest rise times the simulation appears to be slightly faster than the data. This could imply that the simulation Luke phonons reach the detectors too late, in that they are measured too close in time with phonons that should be arriving later. Another possibility could be our model of charge transportation, since the charges are the source of these phonons.

The simulation predicts a longer decay time than measured. This could be a problem with the TES model. If the absorption rate into the TES is underestimated then phonons
will remain in the detector for a longer period of time. The long decay time could also be due to intrinsic phonons entering the ballistic regime. If the simulation underestimates the rate at which phonons down convert, it will also take longer for the pulse to decay.

The simulation predicts the events to reach position independence sooner than measured. This could imply that simulation phonons are not being absorbed at a high enough rate. Instead, of being measured they reflect off the surfaces of the detector and distribute themselves among the other phonons. Whereas, if the simulation TES were to have a high rate of absorption, fewer phonons would be moving through the detector and it would be easier to predict where the event occurred.

These differences seem to be consistent. The second two concern themselves with absorption into the TES’s. Currently, a probability is assigned to determine if a phonon is measured when it reaches a TES. A model of the physics occurring at the detector surface could be implemented to form a more physically realistic representation. The charge model could also be further developed; this should improve agreement in the rise times between data and simulation. Currently, the phonon pulse output is the majority of the analysis. If the simulation for measuring charge were improved it could also be used in the analysis, and could at least help our understanding of Luke phonon production.

ACKNOWLEDGMENTS

This work was conducted at SLAC National Laboratory and was funded by the United States Department of Energy, through the SULI program. I would like to thank my mentor, Rudy Resch, for his guidance and taking the time to explain what I didn’t understand. I would also like to thank Eduardo do Couto e Silva, for checking in on my progress and moving my project along near stumbling blocks. The whole CDMS collaboration at SLAC has been very helpful and supportive of my project; I want to thank all of them. The SULI staff, who worked to make this program run smoothly, provided great lectures for us, and ensured we
had a productive summer. Finally, I want to thank all of my fellow SULI students who made this summer exciting and more than just about research.

REFERENCES


FIGURES

Figure 1: A typical plot of the phonon pulse. The top contains the raw data pulses, the bottom pulses are scaled. A diagram of the sensor regions on the detectors are located in the upper right corner.
Figure 2: A plot of the fastest and slowest risetime for each event. Data is in gray, simulation is outlined in black dotted lines.

Figure 3: The distribution of the decay times for data and simulation.
Figure 4: The time to position independence distributions. Note that they are both skewed to the right.