REU Research Project: A Scaled Simulation of the Super Cryogenic Dark Matter Search

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Working with the Super CDMS Collaboration

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The SuperCDMS Collaboration is one of many groups whose aim is to detect and distinguish the non-visible “dark matter” that comprises twenty-five percent of the Universe’s hypothesized mass. Germanium detectors were specially crafted and organized in order to detect the Weakly Interacting Massive Particles that our planet diurnally encounters, which SuperCDMS aims to correlate with the dark matter of scientific models. A computer simulation of these detectors interacting with particles called SuperSim is employed to model the effects of particle collisions with the detectors using different set-ups and shielding. Analyzing known sources also provides profiles to extradite “noise” patterns so that detector tower layouts and shielding may be improved in the future.

Introduction

A massive halo of unknown, unseen matter that is gravitationally bound to the luminous matter of galaxies is present in many established cosmological models of the Universe [1]. Should the "dark" matter of the universe consist of unidentified particles, our planet would constantly be passing through it, making it possible to detect directly as the Earth (and some detection apparatus beneath its surface) pass through our galaxy's dark matter halo [2]. The primary mechanism through which this could occur is elastic scattering between an incident particle and a nucleus in the volume of some detector material [2, 3, 4]. Utilizing germanium detectors, the Super Cryogenic Dark Matter Search (SuperCDMS) collaboration is searching for "weakly interacting massive particles," also known as WIMPs [2, 4, 5, 6]. The discovery of these particles could revolutionize particle physics and cosmology.

SuperCDMS detectors are designed with the capability of detecting the minute signals within the detector by elastic collisions between detector nuclei and WIMPs [5]. The energy deposited by a WIMP in the detector may be as low as a few tens of kiloelectron volts (keV). The foremost requirement for the properly functioning experiment is that the detector be maintained at a very low temperature to distinguish the deposited energy from the energy of the detector's nuclei. The SuperCDMS project and associated test facilities employ He-3/He-4 dilution refrigerators which are able to achieve detector base temperatures as low as 10mK [2, 4, 5, 6].

SuperCDMS is the successor to the CDMS II experiment, which was located in the Soudan Mine, underground in Minnesota, USA [6]. SuperCDMS plans to be relocated to SNOLAB (Vale Inco Mine, Sudbury, Canada), which is a much deeper facility [4]. The purpose of setting the experiment in underground facilities is to provide shielding from cosmogenic events and, as a result, reduce the interference of known background particles [6]. Isolation from surrounding "noise" increases the chances of having a positive identification of a WIMP and will allow much more stringent limits to be placed on the interaction cross-section of dark matter particles [4, 6]. Many of the simulation and analysis programs being used to analyze background noise signals and detector energy readouts are produced by CERN, and internationally applied. One such program is the *Geant4 Simulation* for the SuperCDMS experiment, which imitates particle collisions through matter [7]. Utilizing this program, different radiation sources were fired at a detector tower configuration resembling that of the Soudan Lab to analyze the "noise" caused by particles from various energy sources passing through the detectors. This process allows experimenters to define the ideal tower and shielding arrangements to minimize “noise” and maximize exposure to WIMP dark matter particles.

The Experiment

Overview and materials

As part of the SuperCDMS collaborative, Saab Lab, led by Professor Tarek Saab of the University of Florida, is responsible for contributing to the search for WIMP dark matter particles. While a Helium-3 dilution refrigerator is present in the lab, much of the work to be performed is on computer terminals running the Geant4 simulation. The specially designed “SuperSim for CDMS” is one such program that is executed from the Terminal workspace of an iMac machine. A Monte Carlo simulation of thousands of particle collisions on pre-designed detector tower configurations is thus run, outputting a text file with thousands of hit coordinates. The data is analyzed using a variety of MATLAB r2009a functions. Depending on the input information for every simulated run, a myriad of plots and histograms are produced and interpreted for experimental purposes.

“SuperSim for CDMS”

The “SuperSim for CDMS” program was created in order to perform accurate Monte Carlo simulations of particle collisions with the Germanium detectors being employed in the CDMS, CDMS II, and SuperCDMS experiments. A variety of experimental variables exclusive to the CDMS experiment are included and may be easily arranged in order to emulate different experimental scenarios. Among the unique qualities that are written into the program are laboratory layouts of the Soudan, Minnesota, and SNOLAB, Canada, mines. Also available are different shielding materials and set-ups. These variables include casing materials, cryostat configurations, and energy sources. Controllable detector configurations and tower patterns are crucial components of the colloquially-called “SuperSim” that allow members of the SuperCDMS collaborative to experiment with the efficiency and isolation of various ideal set-ups. Compounded with the ability to control energy sources, the feature that allows freedom in setting up towers is the key to the evolution of the CDMS project, as it allows experimenters to define the ideal tower and shielding arrangements to minimize “noise” and maximize exposure to WIMP dark matter particles.

A hexagonal tower pattern consisting of five towers of three stacked detectors was the implemented configuration for the CDMS II experiment [2]. A macro (text) file was created—written in the GEANT program language as part of the SuperSim—that emulated this tower design. The relevant shielding and lab configuration were also included in the command program, as well as commands to output a visual image of the tower configurations (**Figure 1**). The process of creating a “macro” file to simulate a specific experiment was repeated three times for two different sources of radiation. The first radiation source was a 300 keV beam being fired at the detectors from a certain position. After that, a source of radiating Pb-210 was placed at the bottom of the third tower.

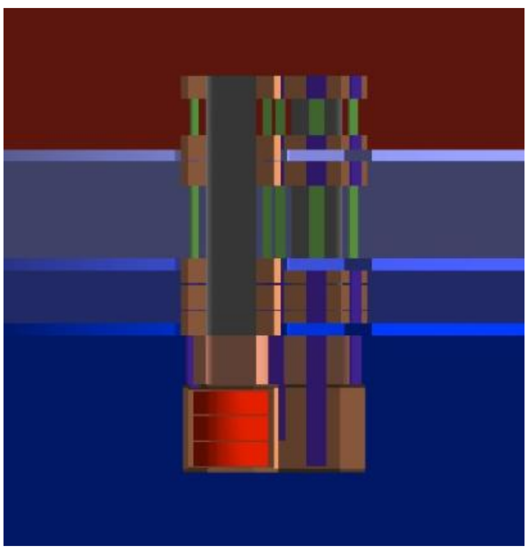


Figure 1: Side view of model detector tower configuration output from the SuperSim Program. The three stacked detectors and surrounding shielding are visible.

MATLAB analysis of data

After SuperSim is allowed to run simulations of particle collisions—sometimes for hours—it outputs a text file comprised of columns of data among which are the locations of particle collisions within individual detectors, the initial energy of each particle, and the energy deposited by each particle in the detector that it collided with. After SuperSim is run, its data is analyzed and plotted. A powerful computing tool like MATLAB was crucial in performing large-scale data analysis.

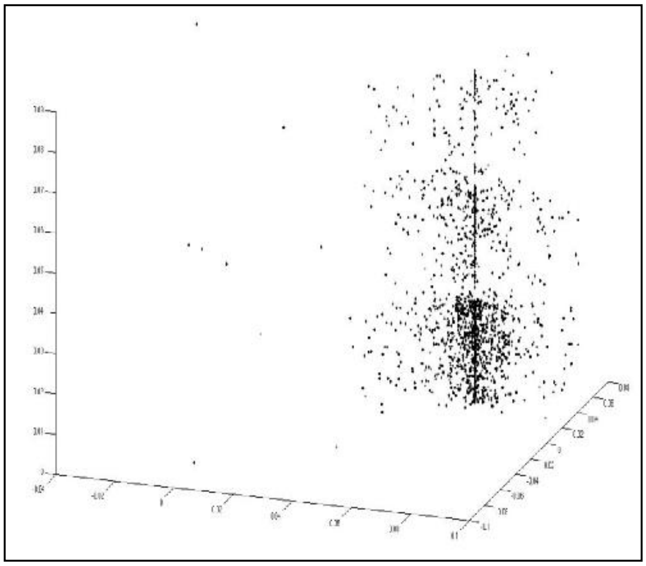
The first task in acquiring constructive results was to import the data that came from SuperSim into MATLAB with the "importdata" function. Once all of the data was extracted from the text file, it was be separated according to detector and the hits from each individual detector were be analyzed and plotted later on. This task was performed by a MATLAB script entitled "DetectorSeparator.m". It was furthermore necessary to add specific vectors to hit-location data points, depending on which detector they were a part of, as SuperSim output data in a fashion that superimposed the data from the fifteen individual detectors onto one detector centered at the origin. "LayoutConfiguration.m" was written for the purpose of scaling data points to elucidate the original tower. Once the original data was filtered by the two aforementioned programs, a plot of the data drawn in three dimensions showed exactly where within the detectors the majority of collisions take place. After the output data from SuperSim was been separated and plotted, a clear picture of what was going on within each detector was available.

Results and Discussion

Source 1: 300 keV Beam

For this experiment, a constant beam constantly churning out 300 keV was fired directly beneath the detectors from a random position. SuperSim was instructed to fire one million particles for this simulation. There was no shielding included in the set-up, so all one million particles must have hit the detectors at some point. When the data points from the simulation were distributed, analyzed, and plotted in MATLAB, it became evident that the effects of the beam were, for the most part, concentrated (**Figures 2 and 3**). A clear vertical line of point collisions marks the perpendicular direction of the beam source near the fourth tower of the setup. Also visible are scattered points of contact throughout other detectors.

What is most useful to gleam from the three-dimensional plot representation of the simulation is the “noise pattern” created by the radiation source. Understanding the effects of various energy sources on the CDMS germanium detectors allows for better data analysis from the actual experimental detectors that are undergoing a surfeit of unknown energy interactions. From the data provided by the SuperSim simulations, better shielding techniques follow a clearer understanding of noise patterns.



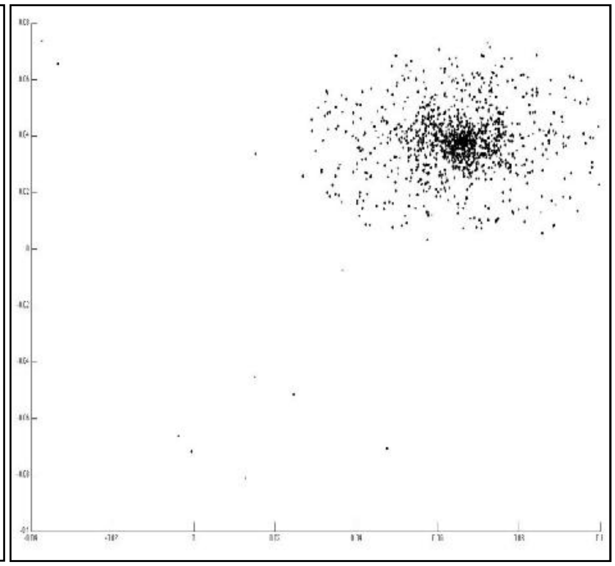


Figure 2: A three-dimensional side-view representation of particle collisions from a 300 keV beam. The outlines of the three stacked detectors of Tower 4 are discernible, as is a straight perpendicular line where the beam is most concentrated. Other collisions are also present.

Figure 3: A top-view representation of particle collisions from a 300 keV beam. A concentration of particles near the center of an elliptical pattern represents a top-down view of Tower 4 being penetrated by energy.

Source 2: Low Background, Pb-210

Placed in the Soudan Lab, the virtual tower configuration was this time fitted with radiating Pb-210 sources on bottom of Tower 3. SuperSim was then instructed to fire ten million particles for this simulation. When the data points from the simulation were distributed, analyzed, and plotted in MATLAB, it became evident that the effects of the sources were concentrated (**Figures 4 and 5**).

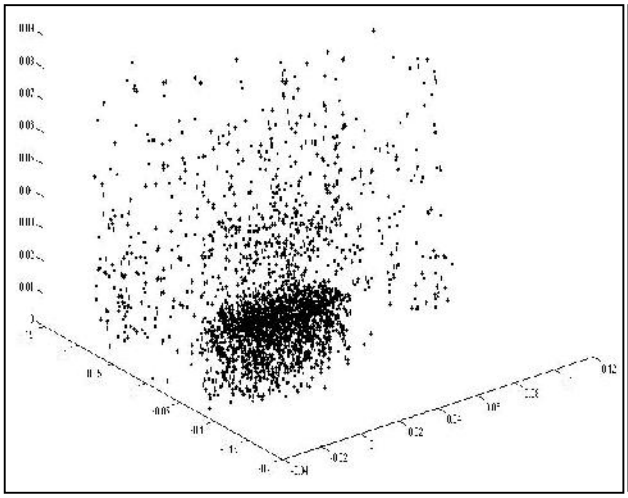


Figure 4: A three-dimensional side-view representation of particle collisions from a Pb-210 source. The outlines of all five towers are discernible, with a concentration of collisions clearly focused on the bottom of the third tower, where the source was placed.

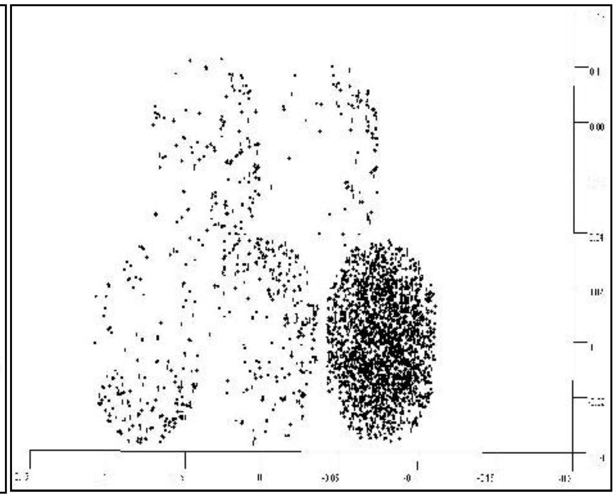


Figure 5: A three-dimensional top-view representation of particle collisions from a Pb-210 source. Tower 3 is the most affected by the source, and the patterns on the remaining towers hints at radiation extending spherically outwards from the source until it strikes a tower.

As was expected, the Pb-210 source at the bottom of Tower 3 exhibited the greatest concentration of collisions. The radiating source produced particles that spread outwards in a spherical manner. A greater concentration of collisions on whatever side was closest to the source attests to this claim, although the bottom detector of Tower 3 took most of the hits. It was deduced from running the same simulation without the lab that, because the source was so close to the detectors, the shielding provided by putting the towers in the context of Soudan lab had little effect. The “noise pattern” created by the radiation source is thus envisioned. Understanding the effects of various energy sources on the CDMS germanium detectors allows for better data analysis from the actual experimental detectors that are undergoing a surfeit of unknown energy interactions. In this case, a hit-pattern that appears to be concentrated in one area and extending outwards can most likely be classified as a radiating source, similar to Pb-210.

Conclusions

As part of the SuperCDMS collaboration, simulations and modeling are indispensible. Dark matter is a still mysterious entity. In turning to the simulated world, however, we erect a much steadier bridge between scientific theory and human understanding. With computer simulations and models, an experiment becomes much more feasible. In this specific collaboration, the collisions of virtually millions of particles were performed and measured by a machine whose precision the evolution of human knowledge cannot presently do without.

While plots elucidate clear patterns out of tremendous messes of data, it is still up to question whether a computer simulation of an event can effectively model the chaotic interactions of the physical world. The matter is one of accuracy, and therein lays the tremendous power of a Monte Carlo simulation, such as SuperSim. Because a million random points can be virtually marked, the future distribution of particles under the same conditions will almost certainly follow the same trend. Running various SuperSim simulations of the same event exemplifies this phenomenon. From the three-dimensional plots of marks being left by a 300 keV source, a noise profile can therefore be created for that energy source and used as a point of comparison when analyzing the physical SuperCDMS detectors. The same is true for analyzing the pattern left by a Pb-210 source located near the tower configuration. Other possible sources of analysis vary extremely widely: from cosmic radiation to neutron beams, or uniform sources to unstable isotopes. An even more fecund opportunity of further research presents itself in programming SuperSim to output the energy values of collision particles as well as locations.

Acknowledgements

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