

***REU Research Project: Simulating neutron interaction with the Super
Cryogenic Dark Matter Search Setup***

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I. ABSTRACT

Dark matter remains elusive to modern science, in spite of attempts to detect it. SuperCDMS, an attempt to directly detect hypothetical dark matter weakly-interacting massive particles or “WIMPs”, has achieved progressive improvements in detection technology, but it is still unclear how the detector will react to actual interactions with WIMPs. Here we report on the use of Geant4, a Monte-Carlo framework, to simulate the SuperCDMS setup and its interaction with low-energy neutrons, which should produce the same response in the detector as WIMPs, and some preliminary results of this simulation, indicating a close match of the simulation to already-established physics for neutrons. This matching of the simulation to actual results suggests the future usefulness of the simulation in enabling a calibration of the detector with low-energy neutrons.

II. INTRODUCTION

Since the 1970s, an increasing number of observations have led physicists to postulate the existence of a yet-undiscovered “dark” matter [1,2]. One candidate for explaining the existence and behavior of dark matter is a hypothetical weakly-interacting massive particle (“WIMPs”), potentially one of the particles predicted by supersymmetry [1,2]. If these WIMPs exist, they would be invisible to light, and would only interact weakly via the gravitational and weak forces [1,2]. Although there is

substantial evidence for the existence of dark matter in the form of astronomic observation, none has ever been detected either as a WIMP or as any other conjectural particle.

Current attempts to detect WIMPs do so either through direct detection, which is the aim of our group (CDMS); by indirect detection, which entails looking for telltale indicators of WIMPs annihilating; or by creation in a collider [2]. Previous implementations of CDMS [3,4] failed to return conclusive positive detection of a WIMP, in spite of technological improvements [5], instead setting limits on the range of potential masses and nuclear cross-sections within which a WIMP could theoretically fall [3,4]. Because the interaction of WIMPs with the detector is not well understood, it is desirable to use low-energy neutrons to model these interactions and calibrate the detector; although the detector can differentiate between interactions with certain particles, it is unable to do so for neutrons and WIMPs [6]. This means that low-energy neutrons can be used as a sort of proxy for how WIMPs might interact with the experimental setup.

Here we report on the use of Geant4 to simulate both the SuperCDMS setup and its with neutrons in the energy range of $\sim 10\text{keV}$ to $\sim 1\text{ MeV}$, as well as some preliminary results of this simulation. The simulation in question generated results that were in line with results for actual neutrons, implying the potential of future usefulness of the simulation to generate data corresponding to neutron behavior.

III. THE SIMULATION

A. SuperCDMS Setup

SuperCDMS used germanium iZIP detectors to search for dark matter [5], enabling greater sensitivity in output data than in previous iterations of the CDMS

experiment. These iZIP detectors are kept in a copper housing and are stacked in vertical columns while detecting, enabling some measure of vertical information from the detector output [7]. The detectors are kept at $\sim 50\text{mK}$ by a cryogenic refrigerator [7] and consequently are rendered capable of detecting precisely due to minute changes in temperature caused by individual events [8].

The detector can differentiate between electron and nuclear recoil, allowing for discrimination between signals from charged and neutral particles, but cannot differentiate interactions caused different neutrally charged particles, for example, neutrons and WIMPs [6]. Because the detector will, in principal, respond to neutrons and WIMPs in the same way, low-energy neutrons, whose behavior is well studied, can be used to gauge how the detector should generally respond to interactions with WIMPs.

B. Code Structure

As it has been elsewhere in the CDMS project [9], Geant4 was to simulate the physics of the experiment, in this case providing a model for the response of the germanium iZIP detectors and other experimental setup to neutrons within a specific energy range.

Geant4 is a C++ physics simulator designed by CERN to approximate the interaction between physical substances and particles [10]. Geant4's extensive pre-made structure features large numbers of potentially-useful materials, particles, physics processes, geometric setups, detector classes, and user interfaces, but it is also engineered to allow a substantial amount of customization of these things in order to achieve a close matching between the behavior of the simulator and the behavior of the physical experimental setup [10].

Geant4 is designed so that, in an individual simulation, the setup will be put through a number of runs, in which a large number of events are simulated and the data from each event collected and output at the conclusion of the run. Each event, in turn, consists of a discrete interaction or related series of interactions that correspond to a particle or group of particles generated at the beginning of the event and the interaction of the particle or particles with the materials. Any given event will ultimately represent a single datum in the data output at the end of the run.

To ensure meaningful variation in data from various events, Geant4 uses randomization to approximate how far the particle will move into the material before it interacts with it [11]; just as sometimes a neutron will interact with a material and sometimes pass through, so in the simulation the neutron beam interacts with materials on the basis of how likely a real neutron is to interact with that material.

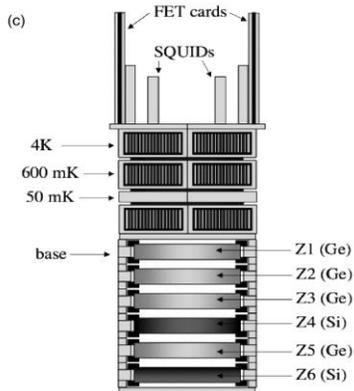
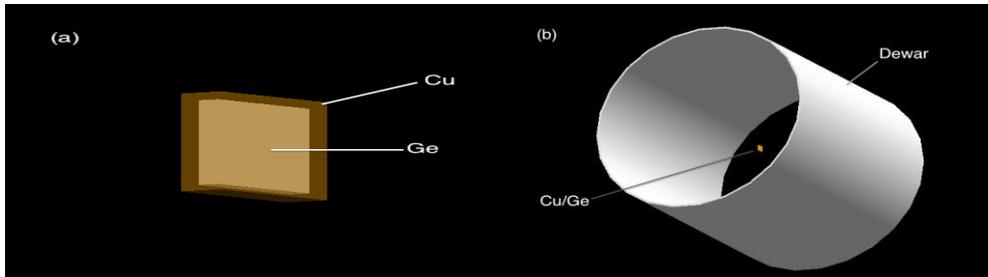


Figure 1: (a) Simulation visualization of germanium iZIP and copper Housing. The germanium is approximated as a $.2 \times 1.27 \times 1.27$ cm cube and the copper housing is a hollow cube with outer faces at $.4 \times 1.47 \times 1.47$ cm and inner faces $.1$ cm removed from the face of the germanium (b) the Aluminum Dewar with copper and germanium inside (c) the CDMS II setup with Ge and Si detectors in tower arrangement [7].

This likeness in output data to an actual experiment enables the accurate prediction of results, potentially allowing for an accurate study of what WIMP detections should look like.

To model the germanium iZIP detector and its housing, our simulation has a $.2 \times 1.27 \times 1.27$ cm cube of Germanium within a $.4 \times 1.47 \times 1.47$ cm cube of copper (fig. 1a). The cryogenic refrigerator is represented by a hollow, Aluminum cylinder which was $.5$ m high with an inner radius of $.495$ m and an outer radius of $.505$ m (cf. figs. 1b and 1c). This setup is surrounded by a series of identical photomultiplier tubes (“PMTs”) which are 15.24 cm high, have a radius of 2.54 cm and are made of He3 at 300 k and variable pressure and density, which required the construction of a custom material (cf. figures 2(a) and 2(b)).

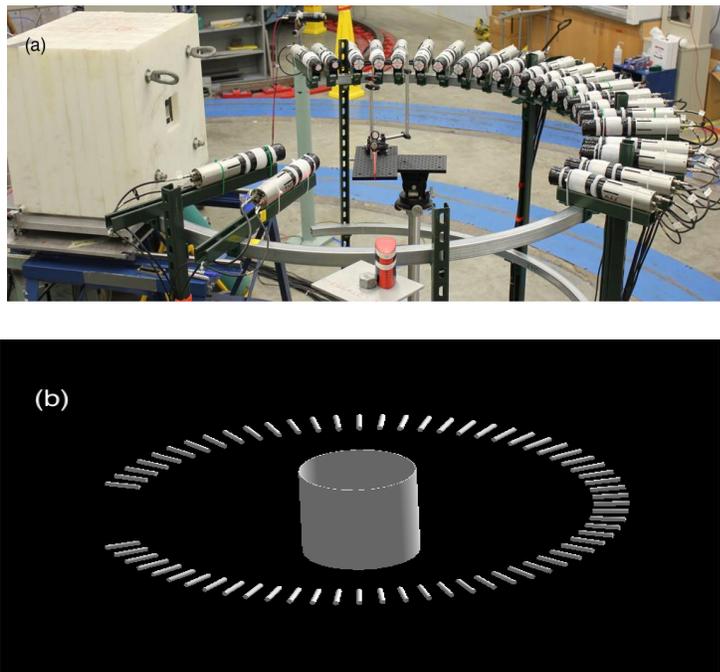


Figure 2:

(a) An arrangement of PMTs being used in an experiment (Image Credit: Rich Barbeau)
(b) 65 PMTs, spaced at 5 degree angles, at a distance of 2 meters from the central setup in Geant4's visualizer.

Because the PMTs of the physical experiment will all be effectively identical, Geant4's parameterization function was used to describe and manage their placements. This meant that in the simulation each PMT was an exact replica of every other PMT

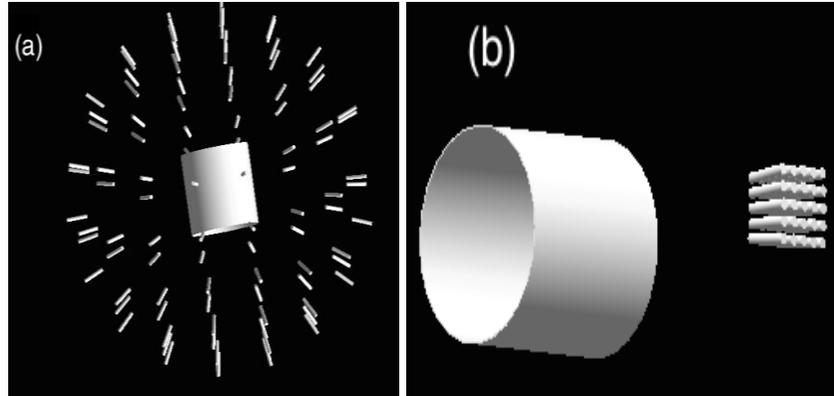
and that the number and positions of the various PMTs were centrally managed by a modified version of Geant4's Parameterized Volume class. To enable differentiation between data read from physically identical PMTs in the simulation, however, each PMT was each given a unique ID number upon creation.

The PMTs were programmed to enable three arrangements, a planar arc arrangement in which the number and spacing of the PMTs can be varied (figure 2(b)), a spherical arrangement of 101 PMTs at regular angular intervals (figure 3(a)) and a "wedge" arrangement of 25 PMTs directly opposite the neutron beam (figure 3(b)). Via Geant4's messenger class, the position, spacing, internal pressure, distance from detector, and arrangement of the PMTs (IE: a sphere, a wedge, or a plane) could all be modified manually by a user, as well as the names of the files output by the simulation at the conclusion of the run and whether all events are output, or only those with energy deposits in the PMTs. Geant4's default user interface also enabled variation in the strength, location, and direction of the beam, and how many events were performed in a given run, which was initiated by the user.

Geant4's primitive scorer class was used for the collection of data from the physical setup; the germanium, copper, and Dewar were all set up to record the number of collisions which happen in each using the "G4PSNofCollision" scorer, the germanium and PMTs were set to record the energy deposited in each using the "G4PSEnergyDeposit" scorer.

Figure 3:

(a) Arrangement of 101 PMTs in a 2 meter sphere around the detector.
(b) Arrangement of 25 PMTs in a wedge 2 meters from the detector, opposite the beam.



To collect time and PMT copy number information, two custom primitive scorers were made, both based on Geant4's pre-existing Energy Deposit scorer. One custom class was used to return the copy number of a PMT if that PMT received any energy from the beam, and a second was used to record the time of a given energy deposit in either the germanium or the PMTs. Finally, Geant4's particle filter was used on all number of collision scorers so that these scorers would return only data caused by neutrons instead of also returning collisions caused by collisions between the atoms constituting a given material.

To collect data on the cross-section of the He3 in the PMTs and the average energy deposited in the PMTs at each energy level, the neutron gun was set right at the surface of one of the PMTs so that the gun fired directly into the PMT. This setup was run for 100,000 events at each energy level.

Data for the scattering angle and the energy deposited in the germanium was collected by setting up an arc of 65 PMTs at 5 degree angles, and firing a beam at the germanium along the line made between the germanium and the middle PMT. This setup was put through a run of 1,000,000 events each to ensure a large enough number of events with detector responses in both the PMTs and the germanium.

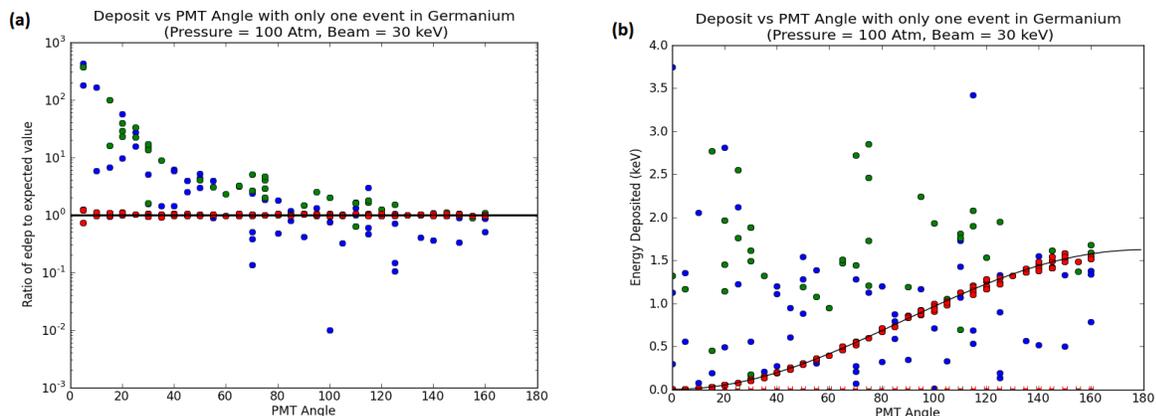
IV. RESULTS AND DISCUSSION

The preliminary results of the simulation show fairly close correspondence of the simulation to accepted physical data from neutrons.

In a rare occurrence (~2% of a million events), the PMTs return an energy deposit value that is much larger than the initial beam energy. In 99% of these cases, the sum of all energy deposits in PMTs is equal to 793 keV. This process is the result of the neutron displacing one of the protons in the He3 within the PMT(s) to make Tritium (H3) and a proton. The corresponding energy absorption of 793 keV is almost exactly equal to the sum of energy released by the formation of Tritium from the combination of a neutron and He3 (764 keV) [13] and the initial beam energy of 30 keV.

When graphed as a function of scattering angle from an uninterrupted beam, energy deposits in specific PMTs roughly correspond to the expected values for the scattering of neutrons off of the germanium nuclei, with a large number of results falling on or along the expected sinusoidal arrangement of data points (figure 4).

Figure 4:(a) The results of the scattering as a ratio to their expected value. Events with a collision in the Dewar or copper are in blue, events with multiple collisions in the germanium are green, all other events are red and the black line represents the theoretical values. (b) The results of the scattering plotted with energy deposited as a function of scattering angle. The event coloring is the same as in (a).



If events that have collisions in the copper or Dewar are excluded from the graph, a better fit to the expected value is achieved. Events with no collisions in the copper and Dewar and only one in the germanium match to the predicted values almost entirely. Almost all events falling substantially below the expected values appear to be the result of scattering off of the copper or the Dewar.

Measurement of the neutron Cross-Section for the He3 PMTs shows a close match to accepted values, exhibiting a peak at 2 MeV (figure 5(a)) that matches the findings of external experimental observations [12]. When the average energy deposit is considered over a large range of beam energies, there is a pronounced spike at or around 30 MeV (figure 5(b)).

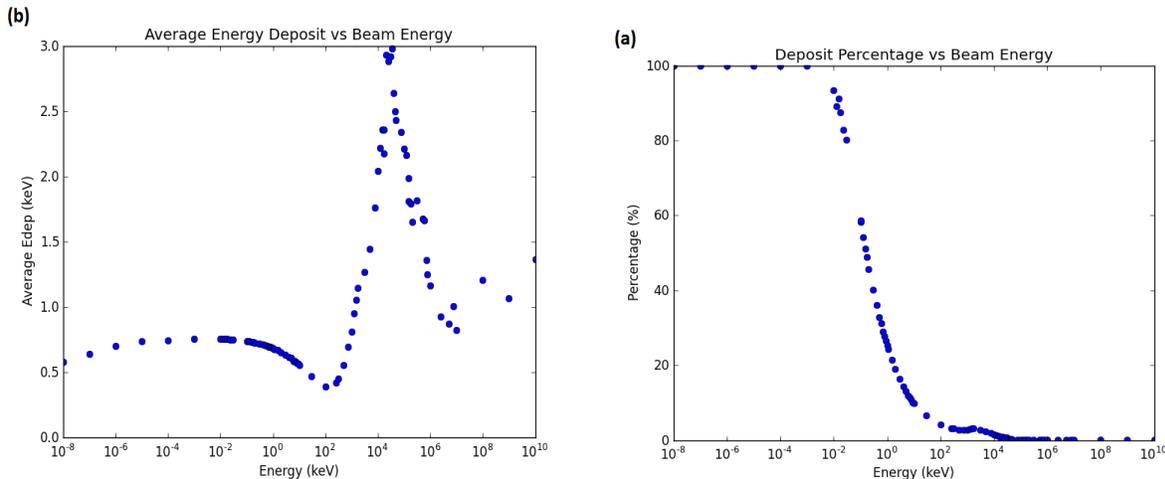


Figure 5: (a) Average Energy in (keV) plotted as a function of beam energy (keV) over the course of 100,000 events.
 (b) Neutron cross section as a percentage of 100,000 events plotted as a function of the beam energy (keV)

V. CONCLUSION

The broad concurrence of expected and actual results for both the scattering data and the interaction cross-section indicate the program's ability to accurately simulate

the physical results of an actual experiment, as do the events producing Hydrogen-3, a result which was not foreseen when the custom Helium-3 material was coded and programmed into the simulation, verifying the accuracy and usefulness of Geant4's simulation of custom materials.

Going forward the simulation should be used to search for meaningful patterns in low-energy neutrons. To that end, the simulation should be used to search for distinctive patterns between output data sets, analyzing, for example, whether there is a correlation between the scattering angle and the time interval between hits in the PMT and in the germanium. These patterns, should they be found, would be useful in forming an idea of what the detection of WIMPs generally is like, facilitating an easier identification of data potentially caused by WIMPs.

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