HAND HELD NEUTRON DETECTOR DEVELOPMENT FOR PHYSICS AND SECURITY APPLICATIONS

An Undergraduate Research Scholars Thesis

by

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ABSTRACT

Hand Held Neutron Detector Development for Physics and Security Applications. (May 2014)

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The Cryogenic Dark Matter Search (CDMS) uses silicon and germanium detectors in the search for Weakly Interacting Massive Particles (WIMP), a candidate for dark matter. Although these detectors are heavily protected with lead and polyethylene, high energy neutrons may penetrate through the shielding and cause nuclear recoils on the detector that may be mistaken for a WIMP interaction event. The purpose of this project was to create a detector that shields as well as tags incoming neutrons to measure the background neutron noise. We present two designs using the high thermal neutron cross sections of boron and gadolinium inside a polyethylene casing. The incoming fast neutrons are produced from the interactions of cosmic radiation with rock. These fast neutrons are slowed to thermal using hydrogenous material such as polyethylene where the thermal neutrons are easily captured by either a gadolinium or boron source. Both boron and gadolinium release ionizing radiation in the form of alpha and gammas upon neutron capture. A boron nitride ceramic was chosen for its high boron density, and the reaction products of alpha particles are detected with a commercially available Ortec alpha detector. Alphas readily interact with matter and are easily blocked with even a very thin material. Because of this, the boron nitride must be positioned directly adjacent to the detector interface, leading to a compact design about 5 inches in diameter and 6 inches in length. To detect the gammas released by gadolinium neutron capture we employ a plastic scintillator that converts the ionizing radiation into visible

light. Bicron 408 converts gammas into visible light with a wavelength of maximum emission at 430nm, which is readout by an avalanche photodiode. Because outside gammas and gammas decay products are indistinguishable in this project, the efficiency of neutron detection will not be determined until the system is tested inside a lead casing in which outside gammas will be shielded. In both regimes, signals will be produced through conventional means and calibration with known sources (Cf^{242}) will allow for approximate energies to be recorded.

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NOMENCLATURE

CDMS	Cryogenic Dark Matter Search
WIMP	Weakly Interacting Massive Particle
APD	Avalanche Photodiode

CHAPTER I

INTRODUCTION

Need for neutron veto system in the Cryogenic Dark Matter Search

The Cryogenic Dark Matter Search uses Silicon and Germanium crystals to detect a candidate for Dark Matter called the Weakly Interacting Massive Particle. These particles do not interact with ordinary matter except through Weak and Gravitational modes. Gravitational Interactions are extremely difficult to detect, and the weak force interaction has been speculated at, but unproven. The primary mode of detection is through collision detection. When candidate particles bump into Silicon and Germanium nuclei in a Nuclear Recoil Event, they simultaneously ionize the surrounding lattice and produce phonons. Charge is extremely easy to detect through specialized circuitry on the surface of the silicon and germanium crystals. Phonons, however, can be slightly more difficult to detect, as they permeate the detector in the form of lattice vibrations and heat flow. By using superconducting Transition Edge Sensors, a very slight change in temperature can be detected, which is the signature of a Nuclear Recoil in the bulk of a Silicon or Germanium crystal. Several other particles produce signatures in these detectors, including neutrons. Every particle except for neutrons can be accounted for and excluded by examining the Ionization Yield. Particles which preferentially interact with electrons rather than nuclei produce three times the amount of Ionization as Nuclear Recoil events, and because WIMPS do not interact with electrons, they will not scatter off of electrons.

Fast Neutrons, neutrons with several MeV of energy, interact with matter in a very similar way to WIMPS. They do not interact electromagnetically, and they recoil with nuclei almost identically to WIMPS. However, while WIMPS are very abundant, having an ambient density of about 2 particles/Liter, Fast Neutrons are not, and so the probability of a neutron leaving a signature in the detectors is much lower than that of a WIMP. Even so, it is very desirable to exclude all neutron signals from the final data collection. The recent results from the CDMS II Silicon Detector quoted background events from neutrons as <0.13 events at the 90% confidence level out of the entire data set. While this is extremely low, improvements must be made to neutron veto and tagging in order to warrant a "discovery".

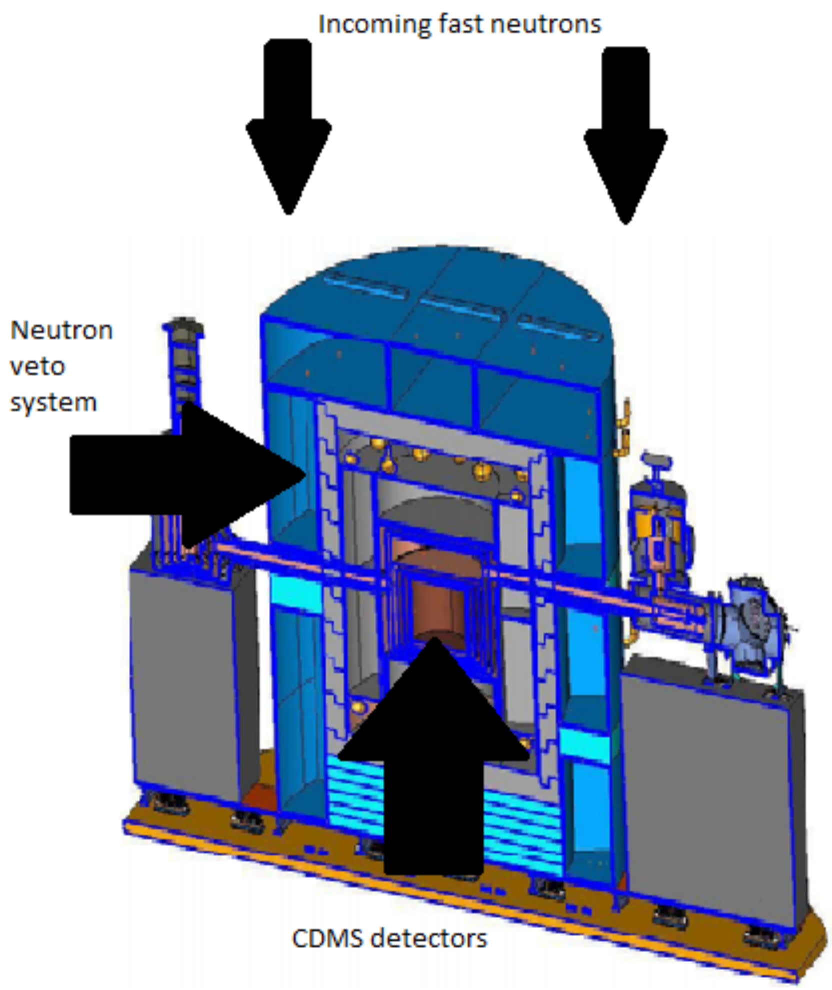

Figure 1: Neutron veto in the CDMS experiment.

The current proposal for a neutron veto system is to surround the detector's outer layers with several inches of scintillating liquid, which, while effective is extremely expensive. Fast Neutrons can be easily slowed by using materials with high proportions of hydrogen like water or plastic. Certain elements are known to be relatively good at capturing neutrons and have been used in the past for radiative therapy due to their radioactive emissions upon capture. Boron 10 in particular is used in radiative therapy because of its emission of alpha particles. Gadolinium, however, has a cross section for neutron capture much greater the cross section for Boron as observed in Figure 1. This quality makes gadolinium a more suitable candidate for use in Neutron veto. Both elements are cheap when found in combination with other materials such as ceramics or plastics.

Isotope	Natural abundance, %	Reaction	Cross section,b	Signatures
^{10}B	19.6	(n, α)	$3.8 \cdot 10^3$	α(1.74 MeV) + ^{7}Li(0.84 MeV)
^{155}Gd	14.7	(n, γ)	$6.1 \cdot 10^4$	γ burst: up to 8 MeV
^{157}Gd	15.7	(n, γ)	$2.6 \cdot 10^5$	γ burst: up to 8 MeV

Figure 2: Cross sections and byproducts of boron and gadolinium.[4]

Boron Nitride is a ceramic material used as an abrasive in machining applications. It is relatively cheap and easily obtainable through chemical distributors. Brittle, but hard, it must be delicately cut using high speed abrasives. In conjunction with an alpha detector, which is commercially available, it provides an effective means of detecting Thermal Neutrons. Gadolinium can be found in plastic commonly used for the protection of electrical circuitry. This plastic can be easily melted into whatever configuration is desired, as its melting point is slightly above the boiling point of water. Gadolinium emits high energy gamma radiation upon neutron capture, and when interfaced with scintillating plastic, these gamma rays can be converted into visible light which can be detected through photodiodes.

Security applications

Radioactive materials that could possibly present as security threats are known to release alphas, gammas, and neutrons. Alphas are stopped by materials as thin as a few microns such as a piece of paper. Lead casing is able to shield gammas, but neutrons need a very thick shell of polyethylene to obstruct neutrons. Because the other signature products of radioactive materials are easily obstructed, a neutron is the product most likely to identify a substance emitting radiation. For this reason, a cost efficient, handheld neutron detector could have potential relevance in homeland security screening. Neutron detectors already in existence are not convenient for inspecting shipping materials or luggage at airports due to size and cost factors. [4] Some current designs include liquid scintillators with PMTs which are large and expensive, and therefore inadequate for large scale application.

CHAPTER II

METHODS

The central objective in the design of our neutron detector is to convert incoming neutrons into decay products we are able to detect by simpler means. We accomplish this with two designs utilizing the high capture cross sections for thermal neutrons of boron and gadolinium. Both boron and gadolinium capture the incoming neutron and release characteristic decay products. When the results of these reactions are detected a neutron capture is confirmed. The advantage to using gadolinium as the capturing agent is the higher cross section (20 times greater than cross section of boron) so a neutron capture is considerably more probable. The disadvantage is that a neutron capture by gadolinium releases only gamma radiation. Although boron has a smaller cross section, boron has the added benefit of emitting alphas in addition to gammas. We used a boron nitride ceramic and Neushield gadolinium loaded polyethylene as the respective boron and gadolinium neutron capture sources.

The neutrons we expect incident upon the detector are on the order of MeVs which is well outside the energy range efficient in capture by boron or nitride. These incoming high energy neutrons need to be slowed to a thermal energy before our sources will have the ability to capture them. This can be achieved by machining a polyethylene cylinder with end caps to encase our scientific instruments. Fast neutrons interact with the hydrogen nuclei in the polyethylene, and the elastic scattering thermalizes the fast neutrons. To slow the high energy neutrons to an energy that best fits our purpose in this design, we determined the necessary polyethylene thickness by calculating the energy moderation due to the polyethylene. [5]

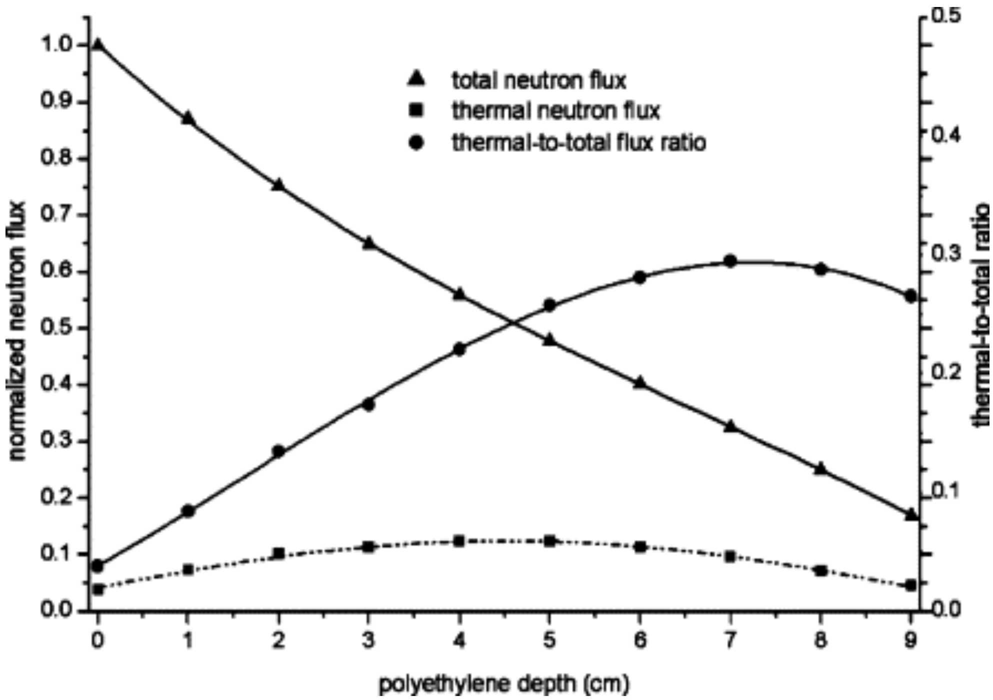

Figure 3: Distribution of thermal neutrons from an incoming neutron flux as a function of the polyethylene thickness. We see that increased thickness stops a portion of the neutrons entirely from penetrating. The thickness also slows a portion of the neutrons to thermal with a peak at around 7 cm. [3]

To conserve space while modulating the most neutrons to thermal as possible, the optimal thickness for our polyethylene shielding was calculated to be 2 inches thick all around.

Important to the veto system applications in the Cryogenic Dark Matter Search experiment is the need for passive and active components in this detector. The passive section of the apparatus is the boron or gadolinium that will converts neutrons into gammas and alphas thereby providing a shield. The active section is the second step in our detector setup where the byproducts are detected so a count of the number of incoming neutrons is formulated. The next step in this detector apparatus is to identify the gammas released from the neutron capture. As seen in Figure 4 both boron and gadolinium release gammas in the region of 0.5 MeV.

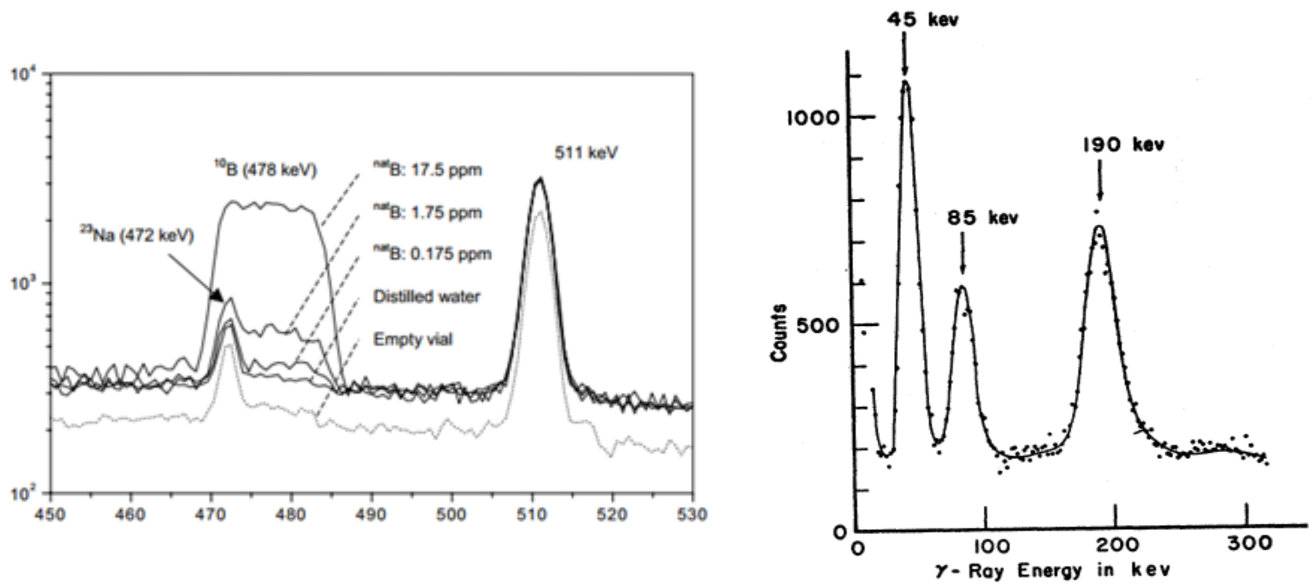

Figure 4: The gamma ray spectra of boron and gadolinium neutron captures respectively as a function of energy. [2]

To detect the gammas once thermal neutrons are captured, a Bicron 408 plastic scintillator with a polyvinyltoluene base converts the released gammas into visible light. The scintillator is excited by the ionizing radiation and re-emits visible light in the 400nm to 500nm region in response.

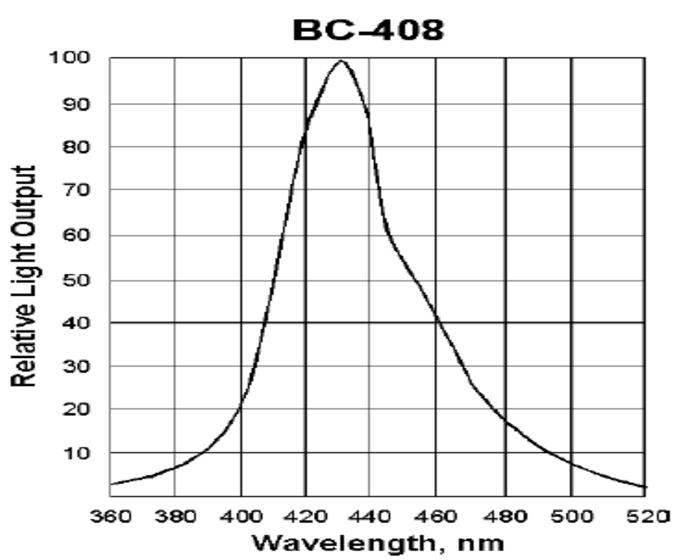

Figure 5: The emission spectrum of the Bicron 408 plastic scintillator.

After having the scintillator machined into two 2" cubes, the surfaces required several hours of hand polishing with various sizes of alumina powders. The polished scintillating cubes were wrapped with 6 layers of Teflon tape (extremely reflective) to keep all light from escaping so that all light emitted reaches only the light detector.

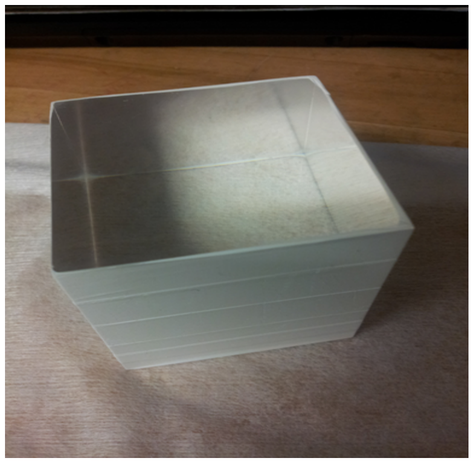

Figure 6: The final machined, polished, and Teflon wrapped scintillator cube.

To readout the visible light emitted from the scintillator, a C30739ECERH series large area silicon avalanche photodiode is employed for its effectiveness in the region of wavelengths released from the scintillator. The scintillator's wavelength of maximum emission occurs at 430nm, and the APD's spectral response is very efficient at this wavelength. The APD is coupled to the scintillator with optical grease, and with the proper preamplifier and biasing, the signals from the APD can be readout on an oscilloscope. When a higher energy pulse is observed on the oscilloscope it is a detection of a gamma indicating a neutron capture occurred. Once the APD was coupled to the scintillator, the scintillator arrangement was tested and proven to identify pulses produced from a known gamma source, Americium 241.

Similar to the gadolinium based detector, the boron based detector utilizes a scintillator design to detect the gammas produced from the neutron capture. In addition, a commercial Ortec Ultra detector is used to detect the alphas emitted from boron neutron capture. With alpha detection along with gamma detection the boron based detector provides a second confirmation of neutron capture. Although this apparatus will capture fewer neutrons because of the smaller cross section of boron, more decay products will be detected because both gammas and alphas will be released and identified.

The next step was to assemble the whole apparatus together and test the efficiency of the neutron detector as a whole. We melted the Nushield gadolinium polyethylene to form a covering for our cubic scintillator, and we cut the boron nitride ceramic into a disk fitted to the face of the Ortec alpha detector. Because alphas are easily blocked in air, the boron source was positioned as close to the alpha detector as possible with the scintillator and APD on the other side of the boron. We positioned our boron or gadolinium source along with the scintillator and APD, and placed all these components along with the corresponding electronics inside the polyethylene cylinder. At this stage the entire setup was ready for testing with a neutron source. Because outside gammas and the gammas released from neutron capture are indistinguishable, the system must be run inside a lead casing where outside gammas can be shielded. The efficiency testing is run inside a mine in India with a Californium neutron source.

CHAPTER III

RESULTS

After the completion of our detector, it was characterized in our lab using low-activity gamma sources. This helped to determine what sort of signals we would be receiving from our photo-diodes. Our detector was sent to India to undergo several months of testing in a mine. This mine is several hundred meters underground, providing excellent shielding from ambient sources. Cosmic rays produce the majority of the neutron radiation we're trying to detect, and so far underground we will be receiving mostly neutron and muon radiation, of which, muons do not interact with our scintillating material. Using LabView-Tektronix software, we will be recording data through the spring, before the detector and data are delivered to us from India. We expect to see data which will show a Gaussian distribution of energies for the neutron radiation. The expected efficiency of detection is expected to be on the order of 50%, as the actual rate of incidence is known for this mine. We will, regardless, compare the average rate over several months of data-taking with the known average to obtain our device's efficiency. This will allow us to establish a statistical confidence in the data which will be gathered by the detector when it is actually used. Error will need to be calculated based on various systematic and statistical sources such as known background noise and known rates of signal producing particles such as background muons. Error produced by defects in the plastic scintillator or capture materials will be difficult to estimate, but will need to be calculated using standard Monte-Carlo Methods.

CHAPTER IV

CONCLUSION

Providing the results that return from the run in India show the detector to be efficient in detecting fast neutrons, steps will be taken to improve our detector and the efficiency of the device. Since the detector is properly detecting neutrons, we hope to invest more time and energy into improving the efficiency to suit the needs of the neutron veto system in the CDMS experiment in the Soudan Mine. We also will be looking into developing the unit into a portable and handheld system that could have future applications in homeland security.

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