Reduction in radioactivity-induced backgrounds using a novel active veto detector for rare event search experiments

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Abstract

The results of a newly developed annular cryogenic phonon-mediated active veto detector are discussed which shows a significant reduction of radioactivity-induced backgrounds in rare event search experiments. The veto detector is made up of germanium weighing ∼500 g with an outer diameter of 76 mm and an inner diameter of 28 mm. The detector can host a 25 mm diameter germanium inner target detector of mass ∼10 g. A GEANT4 simulation with the active veto and inner target detector shows a gamma background reduction of 50 - 80% which is further improved (> 90%) with 4π veto coverage. Experimental measurements with the detector assembly agree well with the simulation.

Contents

1 Introduction

Radioactivity induced backgrounds are one of the major sources of backgrounds in rare event search experiments such as Dark Matter [1], Coherent Elastic Neutrino-Nucleus Scattering (CEνNS) [2], and Neutrinoless Double Beta Decay (NDBD) [3]. These backgrounds mainly come from the radioisotopes present in the material surrounding the detector housing. They are dominantly gammas and neutrons. A passive, multi-layer hermetic shield is used to reduce the background rates of gamma and neutrons. However rejection of in-situ backgrounds present in the detector material itself will create a challenge. One way to reduce these backgrounds is by applying active shielding. We discuss a newly developed phonon-mediated active veto detector which acts as active shielding where an inner target detector is mounted inside the veto detector. The veto detector is able to tag and reduce coincident background events by $> 90\%$. In SuperCDMS SNOLAB, three of the major backgrounds that may limit the sensitivity, are from Compton scatters, surface beta decays from detector housing and background from ^{210}Pb recoil already existing on the detector surfaces from Radon exposure. The active veto detector hosting a inner target can remove these backgrounds from surface betas and the ^{210}Pb recoils and reduce the Compton background by an order of magnitude.

2 The annular active veto detector with inner target

The annular active veto detector is produced with a thickness of 25 mm and the outer and inner diameters are 76 mm and 28 mm respectively. The inner detector which was mounted inside the veto has a diameter of 25 mm and a thickness of 4 mm. The veto and inner detector have a mass of ∼500 g and ∼10 g respectively. Fig 1 shows the active veto with the inner target detector [4]. Both the detectors were produced and commissioned using the same methods as done for standard SuperCDMS detectors [5]. Several challenges that were addressed for instrumenting the detector setup can be found in detail in ref [4]. The major challenges are listed below.

1. Fabrication of an annular veto detector that can host an inner detector.
2. Keeping the inner detector suspended within the veto detector and operating both of them at mK temperatures.
3. Connecting the inner detector circuit to existing cold electronics for signal readout.

2.1 Simulation vs. experimental data

A GEANT4 based simulation was performed with the annular veto and the inner target detector to tag Compton scatter events. An isotropic ^{137}Cs point source was simulated at a distance of 50 cm from the detector. The tagging efficiency, η_{tag} is defined as the ratio of the events that deposit energy in both the inner and veto detector to the total number of events deposits energy in the inner detector. Fig 2(a) shows the result from the simulation where the distribution of energy deposition in the inner detector is plotted in the upper panel and η_{tag} as a function

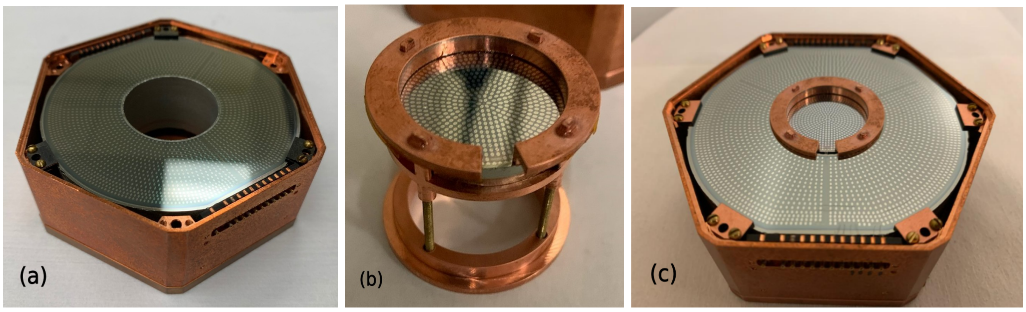

Figure 1: (a) The veto detector mounted in a copper cage, ready for wire bonding followed by cryogenic testing. (b) The copper nest that holds the inner detector. Such a design is chosen for suspending the inner detector inside the veto which also satisfies thermal conductivity between the two detectors. (c) Inner detector nest mounted inside the veto detector. The combined detector setup has a diameter of 76 mm and thickness of 25 mm. All the pictures are taken from ref [4].

of energy deposition in the inner detector is plotted in lower panel. From the figure it is seen that η_{tag} by the veto is expected to be between 50 - 80% [4].

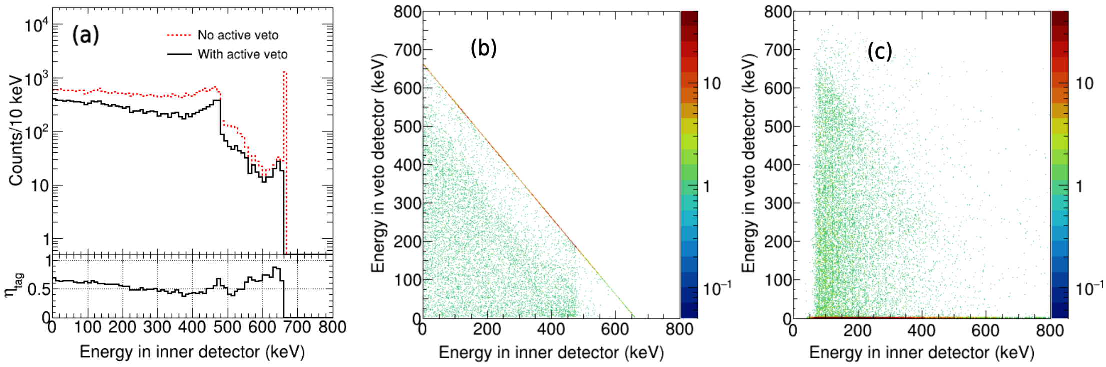

Figure 2: (a) Simulated energy distribution for a ^{137}Cs source (upper panel) and η_{tag} (lower panel) as a function of energy deposition in the inner detector. (b) and (c) show the energy sharing between the veto detector (in the X-axis) and the inner detector (in the Y-axis) from simulation and experiment respectively. The Compton scatter events are tagged through coincidence. Figures are taken from ref [4].

An experiment was performed at the test facility in the Texas A&M University to confirm the ability to tag and veto Compton scatter events. Using a ^{137}Cs source, 662 keV gammas were made to fall on the active veto detector. A comparison between the simulated and the experimental result are shown in fig 2(b) and 2(c) respectively. In the simulation a 662 keV gamma band was seen to be shared between the inner and veto detector. As we had not considered the detector resolution in the simulation, a sharp gamma line is seen whereas in the experimental data we get a smeared distribution due to the detector resolution as seen in fig 2(c). Both the results are qualitatively consistent with each other. A threshold of 70 keV is applied in the experimental data to remove the 60 keV events from an internal ^{241}Am source.

3 Background reduction with 4π veto coverage

3.1 Simulation vs. experimental data

The annular active veto detector, sandwiched between two germanium detectors with similar dimension was simulated using SuperCDMS SNOLAB backgrounds. Using this assembly, one can achieve 4π veto coverage. Fig 3(a) shows the result which indicates that η_{tag} increases by placing the active veto detector with the inner detector between two germanium detectors with an efficiency of approximately 90% in the low energy ($<$ 100 keV) region of interest.

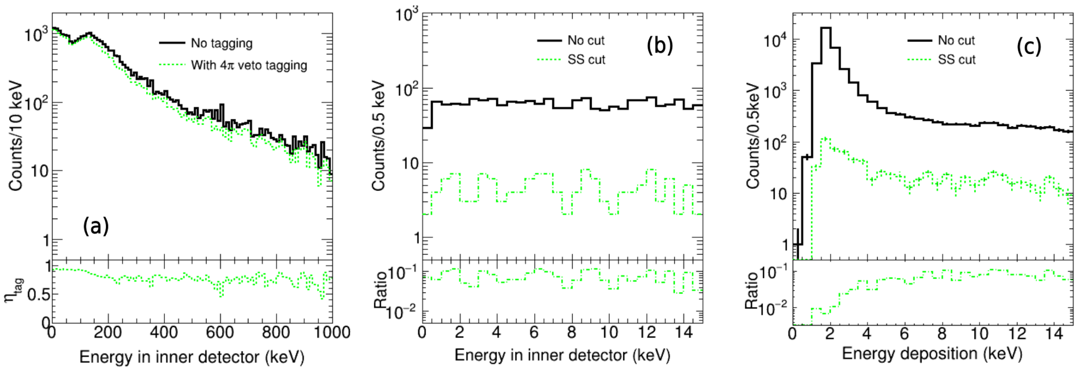

Figure 3: (a) Simulated energy distribution in the inner detector (upper panel) and η_{tag} (lower panel) as a function of energy deposition in the inner detector without veto and with 4π veto tagging show that η_{tag} can be achived $>$ 90% in the low energy ($<$ 100 keV). The upper panels in (b) and (c) show the background spectra in the inner detector with and without SS cut from simulation and experiment respectively. The ratio is plotted in the respective lower panels which show that the background is reduced by an order of magnitude with the 4π veto coverage. Figures (b) and (c) are taken from ref [4].

The active veto detector with 4π veto coverage was characterised at the Mitchell Institute Neutrino Experiment at Reactor (MINER) [6] experimental site. We estimated the energy deposition of single scatter (SS) events in the inner target detector. The single scatter events are identified using three conditions: (i) deposited energy by the event in the inner target should be greater than the noise level of the inner detector, (ii) less than the noise level in the other detectors and (iii) the coincidence time window is $\sim$ few millisecond. Fig 3(b) shows the simulated energy deposition of the single scatter events from the SuperCDMS SNOLAB backgrounds which indicates that background is reduced by an order of magnitude with the 4π veto coverage. Same amount of background reduction is seen in the experimental data taken at the MINER experiemntal site which is shown in fig 3(c).

4 Conclusion

We discussed the work of a newly developed phonon mediated active veto detector made up of germanium. The detector shows a significant reduction in ambient radioactivity-induced backgrounds that are mostly gammas. The results from GEANT4 based simulation of the veto detector agrees well with the experimental results with background rejection efficiency between 50 - 80%. We also show that the rejection efficiency can be improved as high as 90% with 4π veto coverage. Moreover, the detector is capable of rejecting the three concerning backgrounds: surface betas, ^{210}Pb recoils and Compton scatter events by an order of magnitude.

Those backgrounds are expected to limit the sensitivity for the upcoming SuperCDMS SNOLAB experiment. In the future work, we aim to fabricate a germanium veto detector with an inner detector made up of silicon which also shows similar background reduction in simulation [4]. No bias voltage was applied to these detectors. Operating these detectors at higher voltages would help to explore lower recoil energy as low as few eV exploiting Neganov-Trofimov-Luke effect [7,8].

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References

[1] C. Tao, *Dark Matter searches: an overview*, JINST **15**, C06054 (2020), doi:10.1088/1748-0221/15/06/c06054.

[2] D. Z. Freedman, *Coherent effects of a weak neutral current*, Phys. Rev. D **9**, 1389 (1974), doi:10.1103/PhysRevD.9.1389.

[3] A. Zolotarova, *Bolometric Double Beta Decay Experiments: Review and Prospects*, Symmetry **13**, 2255 (2021), doi:10.3390/sym13122255.

[4] M. Chaudhuri et al., *A novel active veto prototype detector with an inner target for improved rare event searches*, NIMA **1039**, 167150 (2022), doi:10.1016/j.nima.2022.167150.

[5] A. Jastram et al., *Cryogenic dark matter search detector fabrication process and recent improvements*, NIMA **772**, 14 (2015), doi:10.1016/j.nima.2014.10.043.

[6] G. Agnolet et al., *Background studies for the miner coherent neutrino scattering reactor experiment*, NIMA **853**, 53 (2017), doi:10.1016/j.nima.2017.02.024.

[7] B. S. Neganov et al., *Application of ionization to heat conversion to the light absorption spectra measurement in silicon at 1 K through adiabatic calorimetry*, J. Low Temp. Phys. **93**, 417 (1993), doi:10.1007/BF00693454.

[8] P. Luke et al., *Calorimetric ionization detector*, NIMA **289**, 406 (1990), doi:10.1016/0168-9002(90)91510-I.