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Ultra-low noise mechanically cooled germanium detector

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ABSTRACT

Low capacitance, large volume, high purity germanium (HPGe) radiation detectors have been successfully employed in low-background physics experiments. However, some physical processes may not be detectable with existing detectors whose energy thresholds are limited by electronic noise. In this paper, methods are presented which can lower the electronic noise of these detectors. Through ultra-low vibration mechanical cooling and wire bonding of a CMOS charge sensitive preamplifier to a sub-pF p-type point contact HPGe detector, we demonstrate electronic noise levels below 40 eV-FWHM.

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1. Introduction

High purity germanium (HPGe) detectors offer excellent energy resolution in a relatively large (kg-scale) format with material purity suitable for ultra-low background experiments. Low capacitance HPGe detectors have demonstrated below 200 eV-FWHM electronic noise [1], leading to applications in the search for dark matter [2] and neutrinoless double beta decay [3].

The direct detection of antineutrinos is another motivating application. Nuclear reactor antineutrinos have unique features which make them attractive for nuclear safeguards [4]: they cannot be shielded, are a direct result of the fission process, and provide information on the operational power and fissile content of reactor cores. Conventional antineutrino detectors operate on the principle of inverse beta decay ($\overline{\nu_e}+\mathrm{p}\rightarrow\mathrm{e}^{+}+\mathrm{n}$), with nuclear reactor demonstrations employing ton-scale liquid scintillators [5,6].

Development of below ton-scale detectors could significantly improve reactor monitoring capabilities. Consideration has therefore been given to *coherent elastic neutrino-nucleus scattering*, whose enhanced scattering cross-section (proportional to the square of the number of atomic neutrons) relative to inverse beta decay provides for several orders of magnitude reduction in detector mass. In this process, a neutrino is predicted [7,8] to scatter off an atomic nucleus. The recoiling nucleus then imparts a fraction of its gained energy (~20% for Ge [9]) to the creation of electron–hole pairs [10] which can then be detected in a suitably low-threshold detector. Typical reactor antineutrino energies (up to several MeV) would yield ionization signals of only a few hundred electron volts, with a greater number of events at lower energies.

The majority of germanium recoils would go undetected in a commercially available HPGe detector with an electronic noise of 150 eV-FWHM [9]. Reducing the electronic noise to 50 eV-FWHM would increase the detection rate by two to three orders of magnitude [11]. The objective of this work is to lower the energy threshold by reducing the electronic noise of the detector–preamplifier system, specifically by reducing the capacitance and temperature of both the germanium crystal and the front end transistor.

2. Ultra low noise detection system

The electronic noise observed at the output of a charge sensitive preamplifier can be described in terms of the equivalent noise charge (ENC) [12], a sum of voltage, $1/f$, and current noise terms:

$$\mathrm{ENC}^2=F_v\frac{4k_BT}{g_m}\frac{C_{\mathrm{in}}^2}{\tau_p}+F_{1/f}A_fC_{\mathrm{in}}^2+F_i(2q_eI_{\mathrm{in}})\tau_p \tag{1}$$

where F_v, $F_{1/f}$, and F_i are voltage, $1/f$, and current noise factors defined by the choice of shaping function [13] respectively.

The voltage noise of the FET is proportional to its temperature T and inversely proportional to its transconductance g_m. The capacitance $C_{\mathrm{in}}=C_{\mathrm{det}}+C_{\mathrm{FET}}+C_{\mathrm{fb}}+C_{\mathrm{test}}+C_{\mathrm{stray}}$ includes all capacitances at the field effect transistor (FET) input: detector, FET gate, feedback, test, and stray. Methods for reducing C_{in} include altering

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electrode geometries to reduce the detector capacitance (C_{det}), selecting a lower input capacitance FET (C_{FET}), and reducing the feedback capacitor (C_{fb}). A capacitor for test pulses (C_{test}) at the input should be a very small fraction of C_{in}. The design of crystal and FET support structures should be carefully planned to minimize the stray capacitance (C_{stray}) to all nearby conductors. The voltage noise term is inversely proportional to the peaking time τ_p.

The $1/f$ noise factor A_f is dependent on dielectric properties and fabrication processes, however its impact on the ENC is significantly reduced in ultra-low C_{in} systems.

The current noise I_{in} includes leakage currents from both detector and FET and is scaled by the electron charge q_e. While not explicitly stated, the leakage current can typically be improved by lowering the temperatures of detector and FET. The current noise term is directly proportional to τ_p. Microphonic noise, not included in Eq. (1), is generally observed at larger peaking time τ_p.

Several issues with existing HPGe detectors may complicate the further reduction of electronic noise. Typical cold front end electronics require some form of thermal standoff, complicating their placement very near the detector, thus increasing C_{in}. Liquid cryogens increase operational complexity and induce microphonic noise from boiling. Extremely low $C_{det}(<1$ pF) HPGe crystals may be difficult to contact with conventional spring-loaded pins. Lower temperatures achievable with mechanical cooling improve leakage current and mobility in silicon transistors and germanium detector crystals, but typical cryocoolers introduce excessive microphonic noise.

To resolve these issues, the system employed in this work comprises an ultra-low vibration mechanically cooled cryostat, housing a p-type point contact HPGe detector, that is wire bonded to a low-capacitance preamplifier-on-a-chip. The design, specification, and assembly of components are detailed in the remainder of this section.

2.1. Low vibration mechanical cooling

While liquid nitrogen (LN_2) is sufficient for cooling HPGe detectors, the lower temperatures (down to 4 K) achievable by mechanically refrigerated cryocoolers [14] are beneficial to leakage currents and carrier mobilities, as the lower phonon population reduces the likelihood of lattice scattering [15,16]. Semiconductor surfaces and electrical contacts made to semiconductors generally have lower leakage currents at lower temperatures [17], thereby reducing noise. At low enough temperatures, charge carrier concentrations at the FET contacts may be reduced to a level where they are said to “freeze out” [18], degrading or preventing operation. At extremely low temperatures, charge trapping in the HPGe bulk may be a concern.

Sub-LN_2 temperatures were achieved in this work with a Gifford–McMahon (GM) [19] cryocooler (model DE-204) from Advanced Research Systems [20]. A 3.5 kW water-cooled compressor was connected through flexible compressed helium lines to a cold head expander affixed to a cantilevered floor stand, while a vacuum cryostat was mounted to a steel table which was isolated from the floor. Vibrations from the significant displacement of the cold head (up to 100 μm at 10 m/s^2 [21]) were eliminated with a scheme employed in low temperature optical microscopy (see Fig. 1) wherein the cryostat cold finger is disconnected from the cold head and heat is instead communicated through atmospheric pressure helium gas. A flexible rubber bellows contains the helium and a 0.5 psi pressure is maintained during temperature transitions through venting or addition of 99.999% pure helium. This configuration achieved its base temperature of 8 K in 5 h, and a Kapton foil heater on the cryostat cold finger enabled operation up to room temperature.

The cryocooler system from ARS was delivered with customizations to their ultra-low vibration optical cryostat (model DMX-20), which was fabricated from nickel-plated aluminum and oxygen-free high-conductivity (OFHC) copper. The cryostat was then further modified to house our detector and readout electronics. The inner 100 mm diameter by 100 mm thick chamber was enclosed by an infrared shield held at the primary stage temperature of ~40 K. Small gaps in the shield were included for pumping, but were minimized to reduce the admission of thermal radiation which would increase the observed detector leakage current. The infrared shield contained an aluminized mylar window, aligned with a 0.33 mm thick beryllium window in the outer vacuum shroud. The cryostat was actively pumped to 10^{-6} Torr to reduce the possibility of contaminant adsorption onto the HPGe point contact surface. Any vibrations from the flexible stainless steel vacuum hose appeared not to have impacted the measured noise performance, as verified by briefly powering down the pump during active measurements.

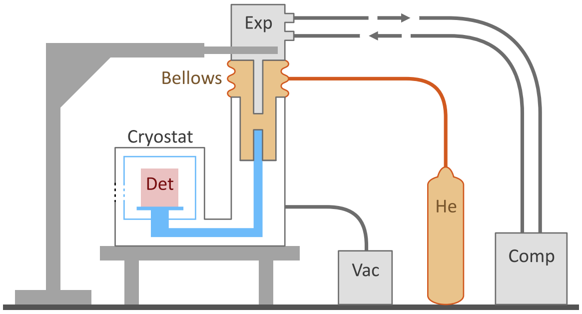

Fig. 1. The ultra-low vibration GM cryocooler consists of a compressor and expander (i.e. cold head) which cool a separate volume of atmospheric pressure helium, which then cools the cold finger of a vacuum cryostat, housing a point contact HPGe detector and front end electronics. The cryostat and expander are mechanically connected only through a rubber bellows.

2.2. Low capacitance HPGe detector

The large volume point contact HPGe detector [22] was originally developed to lower the electronic noise in large mass n-type detectors for the direct detection of weakly interacting particles. The small electrode of this configuration yields a detector capacitance on the order of 1 pF, compared to the tens of picofarads for traditional coaxial germanium detectors. The similar p-type point contact (PPC) detector has found utility in several neutrino and astroparticle physics experiments [9,23].

The PPC HPGe detector used in this work was employed previously to demonstrate the low-noise capabilities of the low-mass front end (LMFE) electronics [24] developed for the MAJORANA DEMONSTRATOR [23]. This 20 mm diameter by 10 mm thick detector originally had a 1.5 mm diameter point contact with a concave dimple for alignment of a tensioned pin contact. The detector previously had a capacitance of 0.47 pF and had exhibited sub-pA leakage current through many temperature and vacuum cycles over several years. The outer n-type hole-blocking contact was formed by lithium diffusion, while the bipolar blocking point contact was formed by sputtered amorphous silicon (a-Si) [25].

The detector described above was modified to obtain a lower capacitance through the combination of an even smaller point contact electrode and the use of wire bonding for the interconnection between the detector and the front end electronics. To modify the detector, the point contact face was hand-lapped (600 grit SiC) to remove the dimple which was incompatible with wire bonding. A 4:1 HF:HNO_3 etch was performed to remove any lapping damage. A new layer of a-Si was sputtered onto the point contact face, and an 8 kÅ aluminum film was evaporated through a 0.75 mm diameter hole shadow mask to form the point contact electrode. The crystal was mounted in a spring-loaded,