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GeMini: The Next-Generation Mechanically-Cooled Germanium Spectrometer

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***Abstract*—**

The next-generation mechanically-cooled germanium spectrometer has been developed. GeMini (MINIature GErmanium spectrometer) has been designed to bring high-resolution gamma-ray spectroscopy to a range of demanding field environments. Intended applications include short-notice inspections, border patrol, port monitoring and emergency response, where positive nuclide identification of radioactive materials is required but power and liquid cryogen are not easily available. GeMini weighs 2.75 kg for the basic instrument and 4.5 kg for the full instrument including user interface and ruggedized hermetic packaging. It is very low power allowing it to operate for 10 hours on a single set of rechargeable batteries. This instrument employs technology adapted from the gamma-ray spectrometer currently flying on NASA's Mercury MESSENGER spacecraft. Specifically, infrared shielding techniques allow for a vast reduction of thermal load. This in turn allows for a smaller, lighter-weight design, well-suited for a hand-held instrument. Three working prototypes have been built and tested in the lab. The measured energy resolution is 3 keV fwhm at 662 keV gamma-rays. This paper will focus on the design and performance of the instrument.

I. Introduction

GeMini is the latest-generation gamma-ray spectrometer based on a mechanically-cooled germanium detector. It is designed for use in a diverse range of field applications where access to power and liquid cryogen may be limited. To that end, GeMini is being optimized for portability and is thus lightweight, low power and rugged.

GeMini benefited from advances made with the gamma-ray spectrometer deploy[1]ed on the Mercury MESSENGER spacecraft [1-3]. For this instrument, limiting the weight and power was extremely important in order to meet the demands of the space mission. It was found that an improved thermal design would help achieve these goals by reducing the demands of the cryocooler. This in turn allowed for a lightweight, low-power compressor to be used. Many of the technologies developed for this instrument make it well suited for a hand-held instrument as well. It was these advances that lead to the GeMini instrument as described here.

II. Instrument Description

A. Germanium Detector

GeMini is based on a high-resolution p-type coaxial germanium detector. The crystal is 50 mm in length by 47 mm in diameter. It has an efficiency of about 25% (relative to a 3" x 3" NaI detector) at 1.33 MeV (^{60}Co). The detector is clamped (30-G preload) inside the innermost infrared shield. The crystal is cooled by the mechanical cooler via a flexible copper braid, which employs electrical isolation to prevent cooler electronic noise from interfering with the detector signal.

Fig. 1. Basic GeMini instrument showing the cryostat, cryocooler (left side) and the combined metal getter and vacuum port (bottom).

B. Kevlar Suspension

The detector is held via a Kevlar suspension system. This serves two purposes: it provides mechanical support to hold the crystal and it provides thermal isolation from the hot outer cryostat.

Therefore, Kevlar (Dupont 29) was chosen for its high tensile strength and low thermal conductivity [4]. The Kevlar fiber suspension system held the detector to a frame and provided support and thermal isolation.

C. Electronic Readout

A rugged internal signal contact brings the detector signal out from the encapsulation to a charge-sensitive preamplifier. The preamplifier is operated with a cooled junction field-effect transistor (JFET) and resistive feedback. Following the preamplifier is a bipolar shaper (6 μs peaking time).

D. Mechanical Cooler

A Ricor K508 Stirling-cycle cryocooler cools the detector. The nominal detector operating range is 85 K. At this temperature, the cryocooler requires 0.9 A at 12 V input. Thus the cooler requires about 10 W at full power. Control of the temperature is achieved with closed-loop feedback using a temperature diode mounted to the detector encapsulation.

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However, as discussed below, it is possible to reduce this power significantly by increasing the operating temperature of the cooler.

E. Radiation Shields

Due to the limited heat lift capability of the mechanical cooler, it was necessary to limit the thermal burden to the detector. The Kevlar suspension system limited the conductive load. However, a significant heat load due to infrared radiation remains. Therefore, infrared shielding was used to limit the thermal burden. This is described more fully in [1].

III. THERMAL LOAD

A key design criteria for this instrument was to minimize the thermal burden as much as possible. A low thermal burden allows for a lightweight, low-power cryocooler to be used. This leads to a smaller, more portable instrument with a longer battery lifetime in the field. All these qualities are important for a hand-held instrument.

Many design elements were taken from the MESSENGER GRS. In addition, other improvements were considered. During the initial design phase, a detailed simulation was done in order to estimate the thermal burden and insure that it was within the power budget for the instrument. A simplified 3-D model of the instrument was made and thermal analysis was performed using a combination of Sinda/Fluint (for conductive heat transport) and a radiation transport program. Table 1 shows the results of the simulations, broken down into major components.

The dominant heat load is the direct infrared impinging on the shielding. However, the combined infrared load on the cold braid and miscellaneous components (such as bolts, temperature diodes etc.) is even greater. This is because these surfaces are not amenable to surface treatment (polishing and plating) and thus have very poor emissivity.

Table 1. Estimated and measured thermal load

Component	Thermal load (mW)
Kevlar suspension	26
Signal wires	15
Low ε IR shields	80
Cold braid	50
Misc. IR load (temp diodes, bolts etc.)	60
Molecular heat load	?
Total (simulated)	231
Total (measured)	175 +/- 25 mW

The table lists the molecular heat load as an unknown. The molecular heat load is the convective (or molecular) transfer that occurs between the hot cryostat wall and the cold detector due to residual gas in the vacuum. It is difficult to estimate this load as the residual gas depends on out-gassing rates and leak rates. Therefore, care was taken to keep the vacuum as high quality as possible. All materials inside the cryostat were chosen for low out gassing properties. This included mainly aluminum and stainless steel but also Teflon where necessary. Materials were kept clean before and during assembly. In addition, all-metal seals were used to minimize the leak rate into the cryostat. Finally, a zirconium alloy getter was used to absorb any residual gasses. The getter is effective for most common gasses except for helium. However, the metal seals are effective at preventing helium from leaking in.

IV. RESULTS

A. Resolution

The resolution was measured using the peak width of gamma-ray lines from standard radioactive sources. Table 2 shows these results for two cases. The first case is with the cryocooler turned off. Because of the excellent thermal isolation of the design, it is possible to operate the instrument for about 30 minutes with the cooler off and still maintain suitable temperature at the crystal. This allows for the best possible resolution since the system is free of microphonic noise. For these measurements, standard unipolar shaping was used with a 6 microsecond peaking time.

The resolution degrades somewhat with the cryocooler turned on due to the influence of microphonic noise. Microphonic noise occurs when the input signal (gate lead to the input JFET) vibrates with respect to ground and changes capacitance. This changing capacitance inject charges into the input, independent of the signal, and is thus a source of noise. This noise can be reduced by standard bipolar shaping circuitry. However, it was found that bipolar shaping was still insufficient to achieve the desired resolution. Therefore, analog "tri-polar" shaping was used. Tri-polar shaping is simply combining the output of a bipolar shaping stage into the input of a unipolar stage. This combined shaping gives excellent resilience to microphonic noise as shown in the last column of Table 2.

Table 2. Resolution vs. energy

Energy	Fwhm (keV) Cooler off	Fwhm (keV) Cooler on
122 keV	1.60	2.95
662 keV	1.96	3.26
1332 keV	2.51	3.60

B. Elevated temperature operation

As mentioned above, the nominal operating temperature of the detector is 85 K. It is usual to operate germanium crystals in the 80 to 85 K range when cooled by liquid nitrogen. However, it is generally not required for them to operate this cold. An exception is when operating in a high-radiation environment, in which case it is desirable to operate them as cold as possible [5-6].

When cooling the crystal with a mechanical cooler, considerable power can be saved by operating the detector at elevated temperatures. The trade off is that the leakage current of the detector is highly dependent on operating temperature. This leakage current is usually insignificant below 100 K but increases rapidly around 120 K. When high enough, the leakage current begins to contribute to the electronic noise and degrades the resolution. Therefore, the goal is to find an operating temperature that balances power savings with the desired resolution.

Note that the power savings from elevated temperature is not a direct thermodynamic savings. That is, the amount of work to operate the detector at 120 K is not much less than operating at 85 K (compared to the 300 K ambient temperature). Instead, the power savings arises because the cooler is operating at the limit of its capability and its efficiency is very low, around 2 to 3%. Raising the operating temperature by 20 to 30 K can easily result in a 50% or more efficiency gain, with a corresponding savings in power.

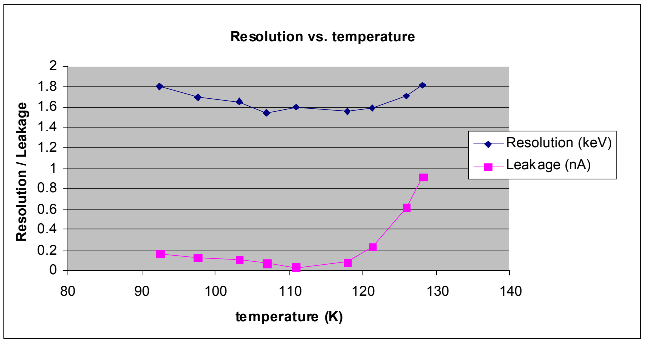

Fig. 2. Resolution as a function of crystal temperature. Also plotted is the leakage current vs. temperature.

Figure 2 shows the resolution as a function of temperature. The resolution if effected by two factors. First is the inherent resolution of the crystal changes with temperature as the leakage current changes. Second, the noise properties of the JFET change with temperature since the internal JFET temperature is not independently controlled. The resolution reaches an optimum value at about 120 K. At this point the leakage current (also shown in fig. 2) begins to rise sharply and the resolution rises as well.

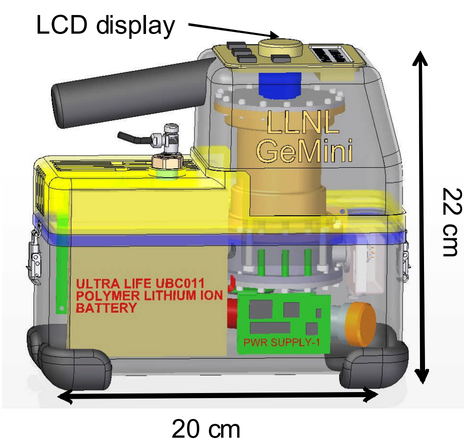

Figure 3. Drawing of the hermetically-sealed housing that will hold the detector and support components.

V. User interface and Packaging

Figure 1 shows the basic instrument including the cryostat and the cryocooler. However, the goal for the complete instrument, including electronics and user interface, to be in small, lightweight package (4.5 kg) suitable for hand-held use. Therefore, the second phase of this project is integration of all support electronics into a hermetically sealed housing. Figure 3 shows the design of this housing. It contains the batteries, high-voltage supply with filtering, preamplifier, shaping amplifier and multi-channel analyzer. It also contains the low-noise power regulation for the preamplifier and control electronics. A small-format microprocessor processes the data. It also controls an on-board LDC display and user interface.

VI. Future work

The GeMini spectrometer has completed its first phase of development. The second phase has begun and consists of developing the user interface and packaging. In addition, advanced features are being developed that will be integrated into future versions of the instrument. One such feature is a rapid cool down capability that allows for cooling the instrument in 2 hours or less. Another is a low-power mode that allows for extended battery operation. This is achieved by operating the crystal at higher temperature, as described above.

Acknowledgment

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VII. References

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[4] Kevlar used: Dupont 29 pre-twisted/braided cord, uncoated (no wax), 12 strand 400 denier approximately .7mm diameter Tensile strength: (breaking) 200 ± 10 lbs. K factor: (conductivity W/m K) = 0.27 @ 150 °K.

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