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Performance of a Gamma-Ray and X-Ray Spectrometer Utilizing Germanium and Si(Li) Detectors Cooled by a Closed-Cycle Cryogenic Mechanical Refrigerator

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Abstract

A mechanically cooled spectrometer has been constructed and tested separately with Si(Li) planar, high-purity germanium (HPGe) planar, and HPGe coaxial detectors. For each of these types of semiconductor detectors, this spectrometer has attained the lowest noise and best resolution at 5.9 keV, 122 keV, or 1.33 MeV of any closed-cycle mechanically cooled spectrometer which has been reported on in the literature. Resolutions at 5.9 keV were 175 eV FWHM with a 4 mm diameter Si(Li) detector and 202 eV with a 16 mm HPGe planar detector. With a 10% relative efficiency HPGe coaxial detector, resolutions of 816 eV at 122 keV and 1.70 keV at 1.33 MeV were obtained.

Introduction

Si(Li) x-ray detectors and HPGe planar and coaxial gamma-ray and x-ray detectors must be cooled to cryogenic temperatures for optimum performance. This has been done almost exclusively by enclosing the detector in a thermally insulated cryostat and cooling it with liquid nitrogen. This method is easy and reliable where liquid nitrogen is conveniently obtained and transported to the detector.

However, a semiconductor spectrometer requiring only electric power to keep it cold is highly desirable for use in remote areas where liquid nitrogen is not readily available or in locations which may become inaccessible for long periods of time. Semiconductor x-ray and gamma-ray spectrometers with nonliquid nitrogen cooling have been constructed in the past, but have rarely been used because of performance limitations. The refrigeration devices used fall into three categories: thermoelectric coolers, Joule-Thompson refrigerators, and closed-cycle cryogenic mechanical refrigerators powered by electric motors.

The thermoelectric cooler does not usually reach temperatures suitable for germanium detector operation (160 K or lower). A temperature of 205 K was obtained by Madden et al. using a small Si(Li) detector in 1978.[1] They achieved a resolution [illegible] 258 eV FWHM at 5.9 keV with a noise of 224 eV FWHM. Madden et al. have recently achieved a 5.9 keV resolution of less than 200 eV FWHM with a thermoelectrically cooled Si(Li).[2]

The Joule-Thompson refrigerator cools by the expansion of a gas in a capillary tube with an incorporated heat exchanger. For detector cooling, very dry, high-purity nitrogen gas from a high-pressure bottle has been used. A pressure of at least 1500 psi is needed for operation. A resolution of 221 eV FWHM at 5.9 keV for a 20 mm^2 HPGe planar detector with Joule-Thompson cooling has been reported by Alberti et al.[3] The use of Joule-Thompson cooling for semiconductor x-ray and gamma-ray detectors has been reported only for small planar Ge and Si(Li) detectors.

Cooling by means of a closed-cycle mechanical refrigerator has significant advantages over other nonliquid nitrogen methods. A much greater cooling capacity allows large coaxial HPGe detectors to be quickly cooled to liquid nitrogen temperature (77 K) or below. Such units can operate for a year or more without maintenance.

However, spectrometers using closed-cycle mechanical refrigerators have previously had very poor resolution compared to those cooled with liquid nitrogen. The major difficulty has probably been the presence of severe microphonics which are electrical oscillations induced at the preamplifier input by mechanical vibrations. Continuous vibrations from the refrigerator have made it difficult to prevent microphonics in a mechanically cooled spectrometer.

In 1973 Marler and Gelezunas reported the performance of a spectrometer cooled by a modified Solvay cycle mechanical refrigerator.[4] A resolution of 640 eV FWHM at 5.9 keV (shaping time unspecified) was achieved with a 30 mm^2 HPGe planar detector. At present, a resolution of about 175 eV FWHM (6 μs shaping time) should be attainable by a liquid nitrogen cooled detector of this size.

Marler and Gelezunas reported on another such spectrometer utilizing a 200 mm^2 HPGe planar detector 5 mm deep.[4] Resolutions of 950 eV FWHM at 22 keV and 1.0 keV FWHM at 122 keV were obtained at unspecified shaping times. Such a detector should achieve a 122 keV resolution of 520 eV FWHM at 6 μs shaping time with liquid nitrogen cooling and up-to-date electronics.

In 1982 Sakai, Murakami, and Nakatani also used a modified Solvay cycle refrigerator with a 50 mm^2 by 5 mm planar HPGe charged particle detector.[5] Their best results were 0.84 keV FWHM (1 μs shaping time) at 60 keV with a cooled FET preamplifier and an antivibration mount, and 2.60 keV FWHM (0.25 μs shaping time) without a cooled FET or an antivibration mount. The resolution of 0.84 keV FWHM at 60 keV is equivalent to about 780 eV at 5.9 keV. A 5.9 keV resolution of about 190 eV FWHM (6 μs shaping time) or 300 eV

FWHM (1 μs shaping time) is achievable for such a detector with liquid nitrogen cooling and a cooled FET.

Even with an antivibration mount, Sakai et al. achieved poorer resolution at longer shaping times (1.06 keV FWHM at 60 keV, 4 μs shaping time).[5] Although Sakai et al. achieved significant improvement by using an antivibration mount, degradation in resolution with increasing shaping time is consistent with the presence of significant microphonics. However, this can be explained in part by the presence of high leakage current (100 pA). Small planar HPGe detectors being used for x-ray and gamma-ray spectroscopy normally have less than 10 pA leakage current.

Clearly, prior results obtained with semiconductor spectrometers using closed-cycle mechanical refrigeration have been poor compared to what is routinely obtained with liquid nitrogen cooling. Although it is uncertain exactly what problems earlier experimenters had, it is evident that microphonic noise has been a major problem which is related to the use of a closed-cycle mechanical refrigerator. However, the measurements reported in this current work have shown that results can be achieved with mechanical cooling which are comparable to those obtained with liquid nitrogen cooling.

Spectrometer System Design

The closed-cycle cryogenic refrigerator used was obtained from CTI-Cryogenics. It utilized a modified Solvay cycle in which the compression and expansion of the working substance (helium) are physically separated. In the CTI-Cryogenics unit, there was a separate compressor unit and cold head which were connected by flexible metal hoses. The hoses used with this spectrometer were 10 feet long. However, shorter or longer hoses (e.g., 100 ft.) are feasible.

The compressor had dimensions of approximately 20 in. by 20 in. by 17 in. tall and weighed 140 lb. When placed on a small dolly, it was reasonably portable. The cold head detector unit with preamplifier and frame was approximately 8 in. by 12 in. at the base and 26 in. tall.

In the spectrometer, a vacuum cryostat contained the cold station of the refrigerator cold head and was connected to the detector cryostat. The detector cooling rod protruded down into the refrigerator vacuum chamber and was connected to the cold station. A resistance heater and silicon diode sensor connected to the refrigerator cold station were available to be used for temperature control. An additional temperature sensor was mounted on the upper part of the cooling rod near the detector mount. The detector, mount, and electronics were of standard EG&G ORTEC manufacture. The end cap was in a vertical configuration. Antivibration mounting was achieved by methods similar to those previously reported by Sakai et al.[5] The complete system with the detector - cold head unit and the compressor is shown in Figure 1.

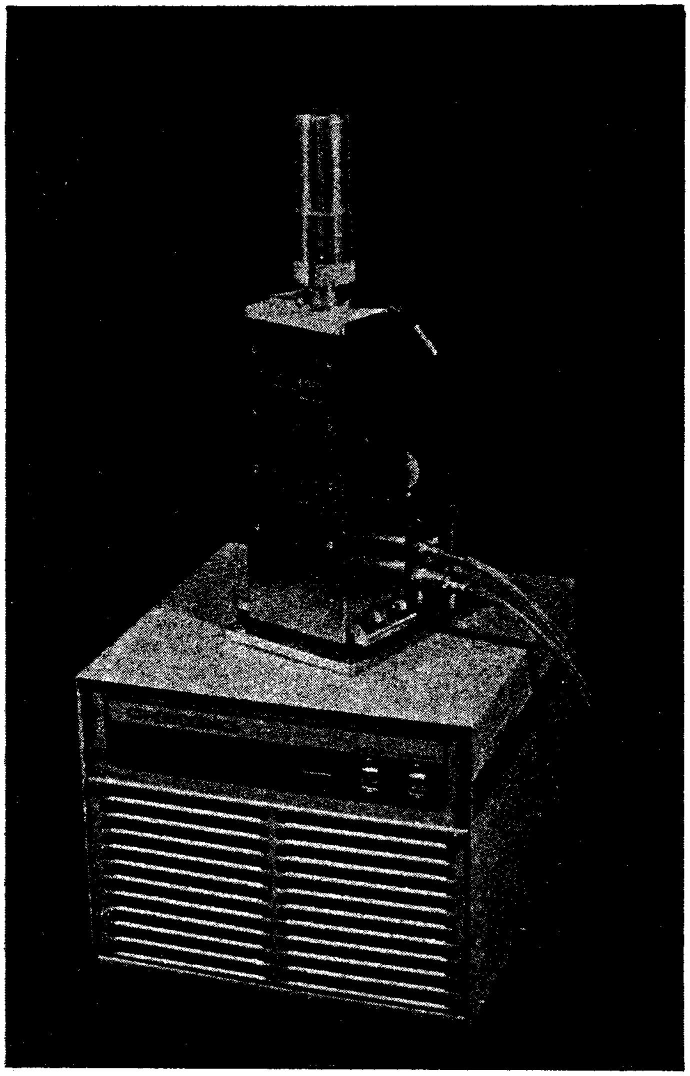

Fig. 1. Detector - cold head unit sitting on compressor.

Thermal Performance

As part of the spectrometer, the CTI-CRYOGENICS refrigerator cooled the detector cooling rod as low as 50 K. A temperature of 55 K was routinely achieved with a 10% relative efficiency HPGe coaxial detector.

Before cooling the spectrometer, it was necessary to pump out the cryostat with a mechanical vacuum pump. Otherwise convective heat transfer would have exceeded the refrigeration capacity and prevented cool down. When the cold station had reached a sufficiently low temperature, an attached quantity of cryosorption agent provided the pumping capacity necessary to maintain a good vacuum. This was needed to provide a suitable environment for the detector and prevent excessive heat transfer.

Cool down times depended somewhat on detector size and on how well the cryostat was pumped prior to cool down. Under typical conditions, a small planar detector cooled from 300 K to 62 K in 3.5 hours. A 10% HPGe coaxial detector cooled from 300 K to 62 K in 5.3 hours. Warm up from 62 K to room temperature took about 2 hours.

Detectors were often operated at the lowest temperature attainable which was in the range of 50 to 60 K depending on detector size, ambient temperature, and the condition of the refrigerator (e.g., the helium pressure). When operated in this mode in our temperature controlled laboratory, the detector cooling rod temperature was found to change only +/- 0.3 K within a 24 hour period.

Detectors were also operated at higher temperature, usually 80 K. The temperature was stabilized by the use of the internal electrical resistance heating element.

Spectroscopic Performance

All measurements were made by using an EG&G ORTEC Model 572 spectroscopy amplifier with the unipolar output routed to an 8000 channel multichannel analyzer. Amplifier shaping was quasi-Gaussian. All shaping times stated herein were the front panel time constants, and all measurements were made with a count rate of about 1000 counts per second.

The spectrometer was first tested utilizing a 4 mm diameter by 4 mm thick Si(Li) detector. Noise and resolution at 5.9 keV were measured repeatedly as the preamplifer, the antivibration mounting, and the temperature were adjusted. The best values obtained were 175 eV FWHM resolution at 5.9 keV and 122 eV noise (10 μs amplifier shaping time). More routinely, values in the range of 176 to 180 eV FWHM resolution at 5.9 keV were obtained with noise ranging from 122 to 126 eV. One corresponding spectrum is shown in Figure 2.

The same Si(Li) detector, mount, and preamplifier would probably have a resolution of 165 eV FWHM at 5.9 keV and a noise of ~110 eV if placed in a liquid nitrogen cooled system. The modest amount of extra noise shown by the refrigerator cooled spectrometer may have been caused by residual microphonics. However, no microphonic response was visible on an oscilloscope at any amplifier time constant.

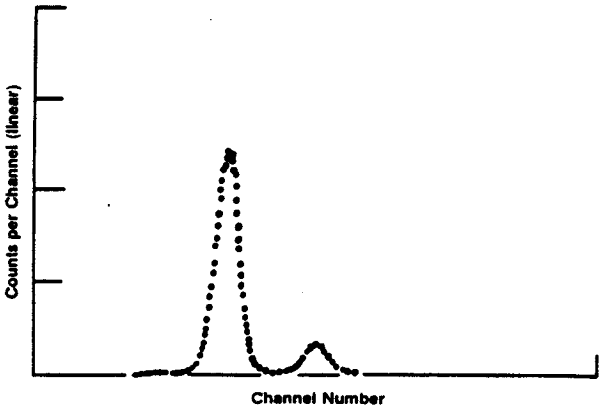

Fig. 2. Spectrum of ^{55}Fe acquired with a 4 mm diameter Si(Li) detector. Resolution is 176 eV at 5.9 keV.

Next, a 16 mm diameter by 10 mm thick HPGe planar detector was placed in the cryostat of the spectrometer. The system was optimized as 5.9 keV resolution and noise measurements were made. The best 5.9 keV resolution obtained was 202 eV FWHM with a noise of 171 eV (6 μs shaping time). More often, values in the range of 207 to 210 eV FWHM resolution at 5.9 keV were obtained with noise values ranging from 171 to 177 eV. A corresponding spectrum is shown in Figure 3.

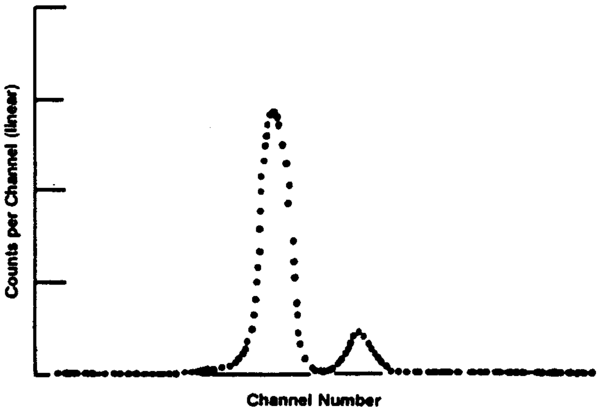

Fig. 3. Spectrum of ^{55}Fe acquired with a 16 mm diameter HPGe planar detector. Resolution is 207 eV FWHM at 5.9 keV.

The same detector and preamplifier if placed in a liquid nitrogen cooled system should have a resolution of 195 eV FWHM at 5.9 keV with a noise of 164 eV. The small amount of extra noise in the refrigerated system was probably the result of a slight microphonic response.

Finally, a 10% relative efficiency p-type HPGe coaxial detector was placed in the spectrometer. At 1.33 MeV, a resolution of 1.70 keV FWHM was obtained (6 μs shaping time). The corresponding noise was 686 eV. A resolution of 816 eV was obtained at 122 keV (6 μs shaping time). Corresponding spectra are shown in Figures 4 and 5. A small microphonic response was visible with an oscilloscope.

This detector, mount, and preamplifier front end had previously been operated in an liquid nitrogen cooled cryostat. Its resolution was 1.65 keV at 1.33 MeV with 571 eV noise (6 s shaping time). The slightly better performance achieved in the liquid nitrogen cooled cryostat resulted from the lack of microphonics in the liquid nitrogen cooled system and the presence of a small amount of microphonics in the refrigerator cooled system.

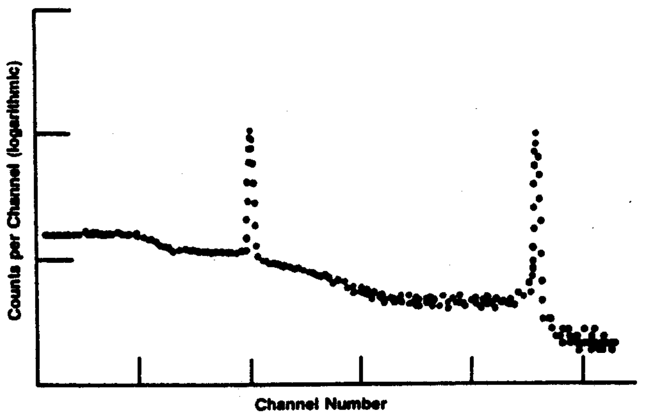

Fig. 4 Spectrum of ^{60}Co acquired with a 10% relative efficiency p-type HPGe coaxial detector. Resolution is 1.70 keV at 1.33 MeV.

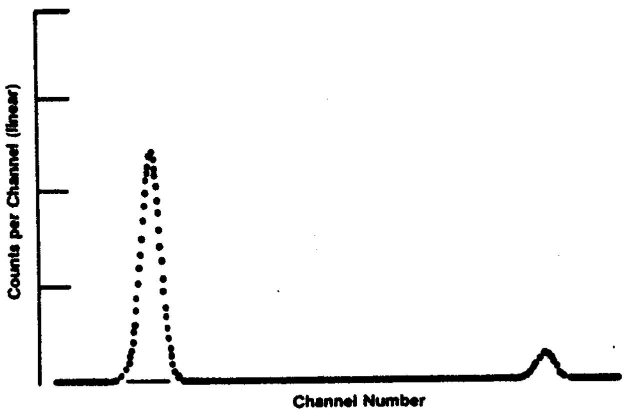

Fig. 5 Spectrum of ^{57}Co acquired with a 10% relative efficiency p-type HPGe coaxial detector. Resolution is 816 eV at 122 keV.

Applications

This mechanically cooled semiconductor spectrometer is useful in any application requiring high-resolution x-ray or gamma-ray spectroscopy in a situation in which liquid nitrogen is not conveniently available or transportable to the spectrometer. This device is useful in remotely located factories, such as paper mills which use x-ray spectrometers as thickness gauges. In the nuclear power industry and in radioactive waste storage, a mechanically cooled gamma-ray spectrometer could monitor an area too radioactive to permit the regular filling of a dewar with liquid nitrogen. Remote waste storage sites, perhaps located deep underground, could also use this type of spectrometer. Such a mechanically cooled spectrometer makes possible high resolution gamma-ray or x-ray spectroscopy on board a ship or even an airplane or a truck equipped with a suitable electric generator.

Conclusion

A semiconductor spectrometer cooled by a closed-cycle mechanical refrigerator was constructed and tested. Resolution and noise values were obtained while using Si(Li) planar, HPGe planar, and HPGe coaxial detectors. Performance was found to be much better than what had previously been reported in the literature for a spectrometer cooled by a closed-cycle mechanical refrigerator. In fact, performance was comparable to that obtained with liquid nitrogen cooling. However, a small amount of extra noise was attributed to a microphonic response to cold head vibrations.

One reason that this device had much better performance than previously obtained with mechanically cooled spectrometers may have been that it had better vibration isolation and damping. However, the same general methods of vibration isolation and damping have been used before.[5] It is also probable that the detectors, detector mounts, and preamplifiers used, although of standard EG&G ORTEC manufacture, contributed less electronic noise and were less susceptible to microphonics than the corresponding components used in previous studies.

The closed-cycle mechanically cooled semiconductor spectrometer reported on here has made possible high-resolution x-ray and gamma-ray spectroscopy in any location which can be suitably supplied with electricity.

Acknowledgements

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