

Mercuric Iodide X-Ray and Gamma Ray Detectors for Astronomy

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1 ABSTRACT

The recent technological developments and availability of mercuric iodide detectors have made their application for astronomy a realistic prospect. Mercuric iodide, because of its high resistivity and high density, can be used in a variety of astronomy instrumentation where high spectral resolution, low noise levels, stability of performance, resistance to damage by charged particles and overall ruggedness are of critical importance. X-ray detectors with areas of 12 to 100 mm square and 1 mm thickness have absorption efficiencies approaching 100% up to 60 keV. The spectral resolution of these detectors ranges from 400 eV to 600 eV at 5.9 keV, depending on their area, and the electronic noise threshold is less than 1.0 keV. Gamma ray detectors can be fabricated with dimensions of 25 mm x 25 mm x 3 mm. The spectral resolution of these detectors is less than 4% FWHM at energies of 662 keV. Because of the high atomic numbers of the constituent elements of the mercuric iodide, the full energy peak efficiency is higher than for any other available solid-state detector that makes measurements up to 10 MeV a possibility. The operation of gamma ray detectors has been evaluated over a temperature range of -20 through + 55 degrees Celsius, with only a very small shift in full energy peak observed over this temperature range. In combination with Cesium Iodide scintillators, mercuric iodide detectors with 25 mm diameter dimensions can be used as photodetectors to replace bulky and fragile photomultiplier tubes. The spectral resolution of these detectors is less than 7% FWHM at 662 keV and the quantum efficiency is larger than 80 % over the whole area of the detector. Details of the properties and performance of the mercuric iodide detectors will be presented and discussed.

Keywords: Mercuric Iodide Detectors, Gamma ray, X-ray, Spectroscopy, Instrumentation, Astronomy.

2 INTRODUCTION

Mercuric Iodide has been investigated for many years for use as a solid state radiation detector that can operate over a wide range of ambient temperatures. The basic properties of the material are very well suited for this application. The wide band-gap of 2.1 eV at room temperature and its small temperature coefficient of approximately 10^{-4} eV per kelvin result in a small thermal carrier generation over a wide range of temperatures. The resistivity of good quality crystalline material is of the order of 10^{12} Ohm.cm or higher. The high density of the material (6.3 g/cm^3) accounts for a large absorption coefficient. The high values of the atomic numbers of the constituent elements (80 and 53) result in a very large photoelectric effect and high full-energy peak efficiency compared with other solid state detector materials, especially at higher gamma ray energies. The high resistivity and the other ionization properties of mercuric iodide result in a low background counting rate compared with other detector systems. This was measured originally by Vallerger et al.(1) operating a detector system on a balloon flight.

The technology to process mercuric iodide raw material and to grow large, high quality single crystals has progressed during the past few years to the point that a variety of detector structures can be fabricated. The performance and properties of several types of detectors, which can have applications in astronomical experiments, will be described in the following sections.

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3 PROPERTIES OF DETECTORS

3.1 X-ray detectors

Constellation Technology fabricates X-ray detectors in two sizes: 7mm x 7mm x 1mm and 11mm x 11mm x 1mm. The smaller detectors have a contact area of approximately 12 mm² and the contact area of the larger detectors is 100 mm². These room temperature devices have a spectral resolution from 400 eV to 700 eV at an energy of 5.9 keV. One of the factors which determines this resolution is the noise generated by the electronics, even when a low-noise transistor reset preamplifier is used. The resolution can therefore be significantly improved by cooling. Figure 1 shows the spectrum of a 12 mm² detector at 0°C.

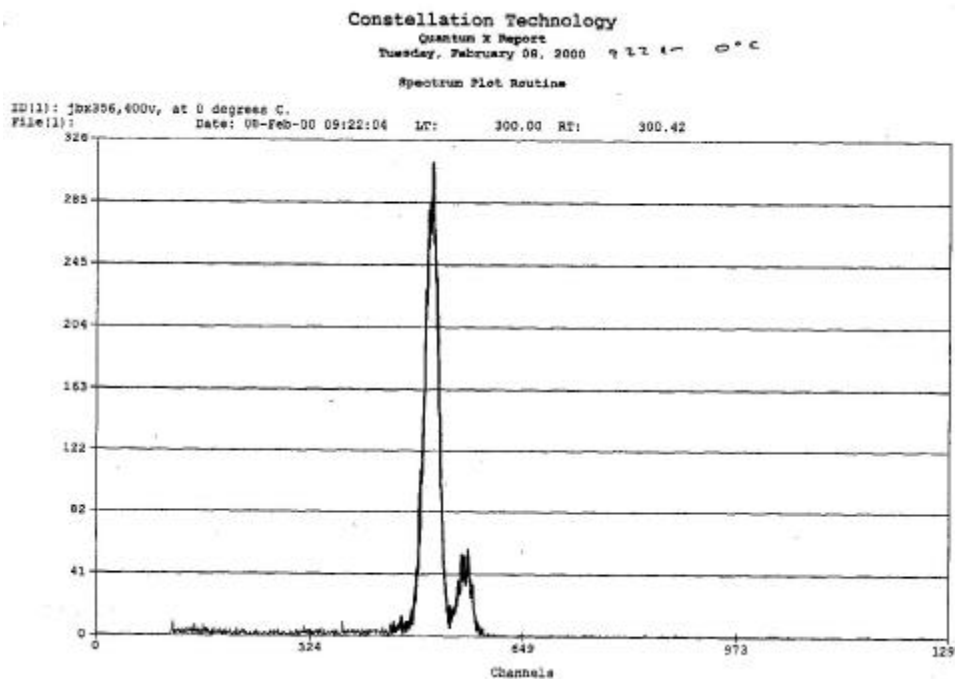


Figure 1. Fe-55 spectrum measured with a 12 mm² cooled detector. The FWHM of the 5.9 keV peak is 216 eV.

The resolution of this spectrum makes it possible to separate the K and L fluorescence lines of many elements of interest in the analysis of soils and surfaces of planets and asteroids. Since the noise level is essentially at the baseline for energies down to 1 keV and below, these detectors will give clear spectral lines of elements like silicon, magnesium and aluminum and even nitrogen at about 800 eV. Spectra identifying these elements have been published before (2), but they were measured at much lower temperatures and with detectors with smaller contact areas of between 2-4 mm² and therefore lower efficiencies.

3.2 Photodetectors

Mercuric iodide is very sensitive to light, and operates as an efficient photon detector in the wavelength range of 400 to 600 nm. Transparent electrodes can be applied to a photodetector which can in turn be optically coupled to a large volume CsI(Tl) scintillator to detect and measure gamma rays. Quantum efficiencies of 85% have been reported for such a device (3) and have also been measured by us. Figure 2 shows the spectrum of a 1 inch x 1 inch CsI(Tl) with a 1 inch mercuric iodide photodetector.

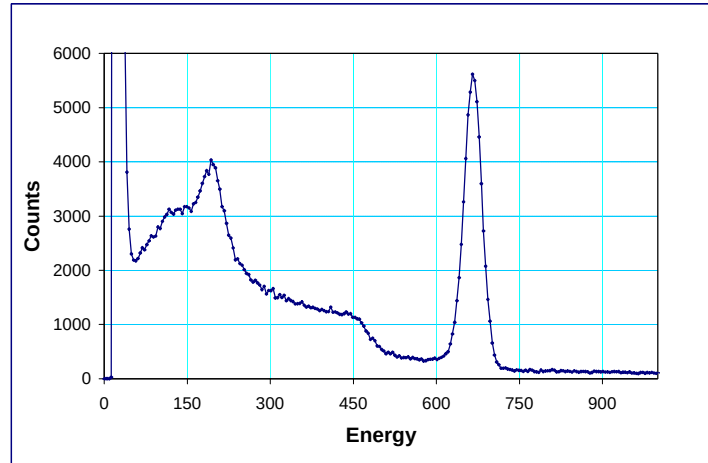


Figure 2. Spectrum of Cs-137 measured with a 1 inch x 1 inch CsI(Tl) scintillator coupled to a 1 inch diameter x 1.7 mm thick mercuric iodide photodetector. Detector bias is 500 V. Full energy peak resolution is less than 6% FWHM.

This scintillator/photodetector combination has demonstrated stable resolution, leakage current and efficiency through more than a year of periodic voltage cycling. The performance in terms of spectral resolution, leakage current and peak efficiency remained stable.

An attempt to couple a 1-inch diameter photodetector to a 2-inch x 2-inch scintillator proved unsuccessful due to the poor optical efficiency. A 2-inch x 2-inch photodetector array, consisting of square detectors, is therefore being developed. This combination could serve as the primary central detector in a shielded space-based system.

3.3 Gamma ray detectors

Typical gamma ray detectors fabricated at Constellation have a contact area of 25 mm x 25 mm and a thickness of about 3 mm. These dimensions result in an active volume of approximately 1.8 cm^3 . The energy range over which spectra have been measured extends from 25 keV to 3.2 MeV. A typical result is shown in Figure 3 (4).

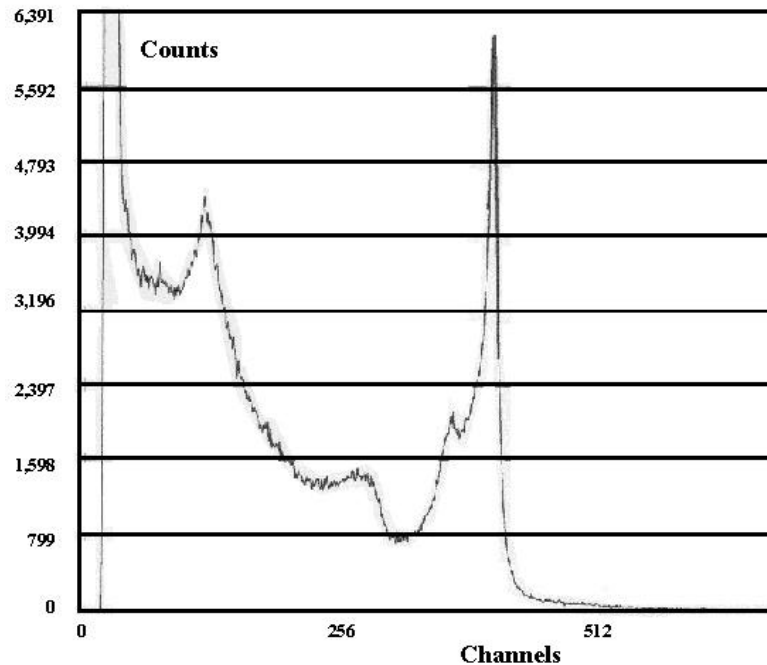


Fig. 3. ^{137}Cs spectrum of detector 81128B11. Contact area 25 mm x 25 mm; thickness 2.89 mm. Bias 2800 V. FWHM 3.3 %.

The high photopeak efficiency of the mercuric iodide and the good spectral resolution of these detectors results in a Minimum Detectable Activity (MDA) which is approximately two times of the MDA of a 2-inch x 2-inch Na(Tl) detector (5).

The full-energy peak in this spectrum is not completely symmetrical but shows broadening at the low-energy side. The mercury escape peak rides on this low-energy tail. This effect is due to incomplete charge collection of the holes. At high energies the gamma ray absorption occurs homogeneously throughout the detector, so some holes have to travel through the total thickness of the detector. With an average hole mobility of approximately $4 \text{ cm}^2/\text{Vs}$, full charge collection in these detectors can take as long as 8 microseconds. When used with standard semi-Gaussian shaping amplifiers, mercuric iodide detectors frequently exhibit ballistic deficit which degrades their apparent resolution. This problem has been resolved by the use of gated integrator amplifiers, which easily compensate for ballistic deficit. Furthermore, recent improvements in material processing have increased the average hole lifetimes, greatly alleviating the problem of charge trapping. Recent detectors of this thickness generally have an energy resolution of less than 2% FWHM and resolutions less than 1.5 % have been measured (6). The incomplete charge collection of the holes can of course also be avoided by reducing the thickness of the detector. Because of the high absorption of mercuric iodide, thinner detectors still provide a high efficiency at energies below 200 keV. For higher energies the effective volume of the detector system can be increased by using multiple detectors in arrays or in stacked configurations.

3.4 Stacked detectors

Several detectors have been combined together by placing them on top of each other in a stack. The detectors used a common voltage source and the signal lines were connected to a common preamplifier and electronic pulse processing system. A photograph of a 4-element stack is shown in Figure 4.

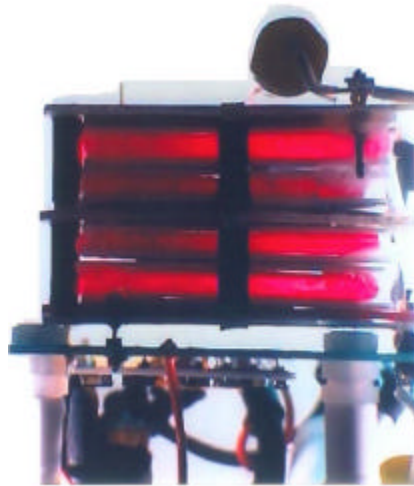


Fig. 4. Photograph of a 4-element stack configuration with common bias and signal connections.

The combined effective volume of the stack is approximately 4 cm^3 . We prefer the stacked arrangement to the flat array because the different detectors are in very close proximity to each other so that escape peaks and Compton-scattered photons exiting from one detector have a very high probability to be captured in neighboring detectors. This feature increases the efficiency of the full-energy peak and tends to reduce the Compton and escape background. As a result, the stack often has a better resolution than the individual detectors. Figure 5 shows a ^{137}Cs spectrum of a stack made from detectors with spectral resolutions of about 6% FWHM, as measured with a semi-Gaussian amplifier.

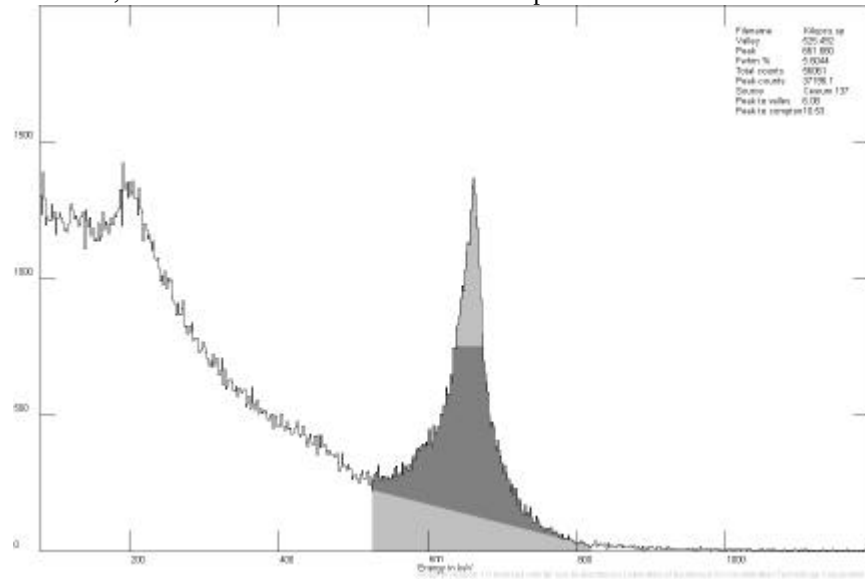


Fig. 5. ^{137}Cs spectrum of a stack of four detectors. Resolution 5.6 % FWHM. Bias 2400 V.

One can see from the spectrum that the mercury escape peak has essentially disappeared. The noise caused by the increased total leakage current has no significant effect on the performance of the detector system.

The next stage of these experiments will be to provide each detector with its own preamplifier and sum the signals based on a timing system. In this way, especially when more single detectors are combined in the stack, it will be possible to monitor the coincidence of the different signals and reduction of the scattering noise and rejection of charged particle interactions may be achievable. In that case it will be possible to avoid the use of an active shield, and the whole weight of a detector module on a satellite could be used for active gamma ray measurements.

4 SUMMARY

The technology to fabricate on a routine basis mercuric iodide detectors with stable performance has advanced to the point where a variety of detector structures is available for application in x-ray and gamma ray astronomy. The advantages of mercuric iodide are the large absorption coefficient, the high full-energy peak efficiency and the low leakage current noise. An additional positive factor is the high resistivity of the detectors to neutron and charged particle fluxes (7). Single detectors can be combined in arrays or stacks to increase the overall efficiency of the detector system. Of special interest is the use of stacked detectors with independent signal electronics for each detector. This arrangement allows for the suppression of escape peaks and Compton scattering and the rejection of charged particle excitation by means of coincidence timing. Gated integrator systems have been designed to improve the hole collection signal in thick detectors.

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