Y/DX-2534

HotSpotter ^{TM} Neutron/Gamma Detector

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April 2003

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HotSpotter™ Neutron/Gamma Detector

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ABSTRACT

The HotSpotter™ Neutron/Gamma Detector combines in a single detecting module high sensitivity to gamma rays up to 3 MeV and sensitivity to neutrons. Using a 15 mm cubic $CdWO_4$ (cadmium tungstate) crystal mounted on a 25 mm photomultiplier, the instrument realizes a factor of 5 increased photopeak efficiency over NaI(Tl) at 1 MeV, and a factor of 2 improvement over CsI(Tl). The addition of a 0.5 mm layer of ^{10}B- impregnated epoxy covering the crystal provides neutron sensitivity without sacrificing gamma ray spectroscopic characteristics. Neutrons are detected by the presence of the 478 keV gamma from the $^{10}B(n,\alpha)^{7}Li^{*}$ reaction. In this paper, we describe the electronics and software of the instrument, and some of its characteristics.

INTRODUCTION

The detection and characterization of radioactive material is an important aspect of safeguards and security. Instruments performing these functions find application in screening packages for radioactive materials, personnel or area dosimetry, criticality alarm systems, portal monitoring, and tamper indicators for stored uranium and plutonium. The usual implementation is via sodium iodide scintillator, and although these detectors are fairly robust (7% resolution at 661 keV) and inexpensive, sodium iodide is sufficiently inefficient above 1 MeV that other crystals become attractive.

Cadmium tungstate is a dense (7.9 g/cc) inorganic crystal with high average atomic number. It is not hygroscopic (and therefore does not require hermetic sealing), and is readily available as rectangular prisms. At 1 MeV, the photoelectric contribution to its linear attenuation coefficient is $0.0590\ cm^{-1}$, while it is $0.0129\ cm^{-1}$ in sodium iodide. Thus, at high energies, an improvement in photopeak efficiency by a factor of 4.6 results from the substitution of a cadmium tungstate crystal equal in size to a sodium iodide crystal. This improvement in photopeak efficiency makes it possible to detect peaks in pulse height spectra with smaller, lighter detectors.

Cadmium tungstate's high photopeak efficiency enables thermal neutron detection through the detection of the 478 keV gamma ray resulting from the $^{10}B(n, \alpha)^{7}Li^{*}$ reaction[1]. When clad with a thin, ^{10}B-rich material (such as 0.5 mm of boron-impregnated epoxy), the gamma rays from the reaction have approximately a 50% probability of entering the crystal, where they are detected with a probability dependent on the size of the crystal. For 15 mm cubes (the size used in HotSpotter™), the efficiency is approximately 37%, resulting in an overall thermal neutron detection efficiency of about 18%. The presence of a thin layer of low-Z, low-density cladding does not significantly affect the spectroscopic properties of the crystal.

The HotSpotter™ is designed as an inexpensive hand-held, battery-powered instrument to implement gamma ray spectroscopy and neutron detection with a single detector. The use of a single detector decreases the part-count and extends battery life by reducing power requirements. The devices in the final stages of development and it has been demonstrated to detect and identify ^{137}Cs, positron annihilation radiation (511 keV), and ^{235}U. The remainder of this paper describes the analog and digital electronics and firmware of the instrument.

ANALOG ELECTRONICS

Radiation detection is accomplished by a $CdWO_4$ scintillation crystal mounted on a Hamamatsu R1924 photomultiplier tube. A negative high-voltage divider string (Hamamatsu E2924-500), putting the cathode between –900V and –1250V and having an unloaded anode terminal, powers the photomultiplier tube. Consequently, the first stage of amplification is an DC-coupled transimpedance preamplifier with a DC gain of 7500 V/A and a single-pole (0.75 µs) transfer function. The unipolar shaping amplifier is implemented as a four-pole low-pass amplifier with unity dc gain. Each pole is set at 1 µs, providing a system transfer function when combined with the preamplifier of

$$\frac{V_{OUT}}{I_{IN}} = \frac{7500}{(1 + j\omega)^4 (1 + 1.33 j\omega)},$$

where ω is in megaradians per second. The preamplifier/shaping amplifier circuits provide a positive-going unipolar output when driven by the PMT anode with a peaking time of approximately 3 µs. The shaping circuit drives digitally controlled, variable gain and offset stages. The offset can be varied between –0.5 and +0.5 volt in 64 steps; the gain can be varied from 0.67 to 2, also in 64 steps.

The shaping circuit also drives a leading-edge threshold circuit set just above the noise level. This threshold circuit generates a logic 1 as long as the signal is above the threshold voltage; it drives the J-input of a J-K flip-flop (the RUN flip-flop). The shaping circuit output also drives a differentiator that in turn drives a zero-crossing detector to trigger at the peak of the shaped pulse and clock the flip-flop. With the K-input at logic 0, the flip-flop's output switches from 0 to 1 (if J = 1) or remains unchanged (if J = 0). The latter is important since it serves to provide a measure of noise immunity by allowing the circuit to ignore pulses of insufficient magnitude. Legitimate pulses arriving during conversion, or prior to readout by the microcontroller are also ignored, since the flip-flop is already set.

The rising edge of the RUN flip-flop triggers a 10-bit ADC (Maxim 1242) driven by the output of the gain and offset stage. It also triggers a monostable that in turn pulses an interrupt line of the microcontroller to signal the processor to read the ADC value. After reading the ADC, the microcontroller resets the flip-flop. This handshake guarantees that the microcontroller reads the converted value associated with the pulse that triggered the circuit.

DIGITAL ELECTRONICS

The integrated components in the digital circuit are low power surface mount parts operating at 5.0V logic levels. A block diagram of the main components of the digital subsection is shown in Figure 1, below.

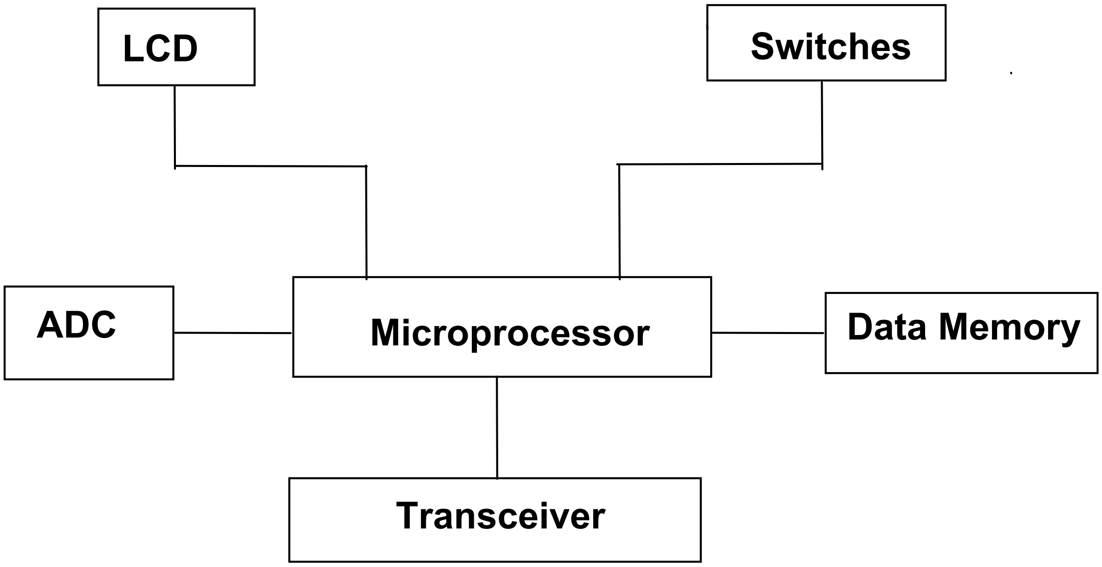


Figure 1, Digital Electronics Block Diagram

The device is controlled by a 12 MHz Philips Semiconductor P89C51RD+ microprocessor having 64K bytes of code memory and 1K byte of random-access memory (RAM). An additional 32K bytes of static RAM is provided by a Cypress CY62256 static RAM interfaced to the microprocessor through a 74VHC373 octal D latch. A Xicor X25642 non-volatile 8K byte RAM is interfaced to the microprocessor by a serial peripheral interface (SPI). A Maxim MAX814K microprocessor supervisory circuit controls the microprocessor's power-on reset and low-power reset.

The analog-to-digital converter is a Maxim MAX1242 10-bit ADC interfaced to the microprocessor through a serial peripheral interface (SPI). A Xicor X9410 quad digitally controlled potentiometer is interfaced to the microprocessor through the SPI. Two of the 10 kΩ potentiometers control the gain and offset stages mentioned previously; the other two are unused. A Maxim MAX3223 RS-232 transceiver was included for uploading spectra, testing and diagnostics purposes.

An Optrex DMC16207 LCD, configured as 16 characters by 2 lines, is interfaced to the microprocessor for displaying operator text information. The microprocessor is also interfaced to two push buttons that are used for operator input. A power on/off switch is provided external to the device enclosure.

The analog and digital circuits share the printed circuit board. Positive voltage for both the analog and digital sides is provided by two Maxim MAX883 +5V regulators; negative voltage for the analog side is provided by two Maxim MAX664 –5V regulators. High-voltage for the photomultiplier is generated by a Hamamatsu model C4900-01 high voltage converter supplied by an LM7815 +15V power supply regulator. The photomultiplier operates from –900 to –1250V; the high-voltage is adjusted manually through a potentiometer. Four 9-volt batteries supply power to the entire unit. The complete unit is shown alongside a 6-inch ruler, below.

Figure 2a. HotSpotter™, closed

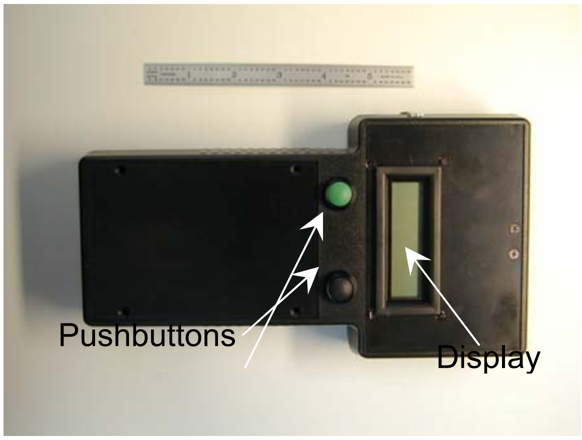
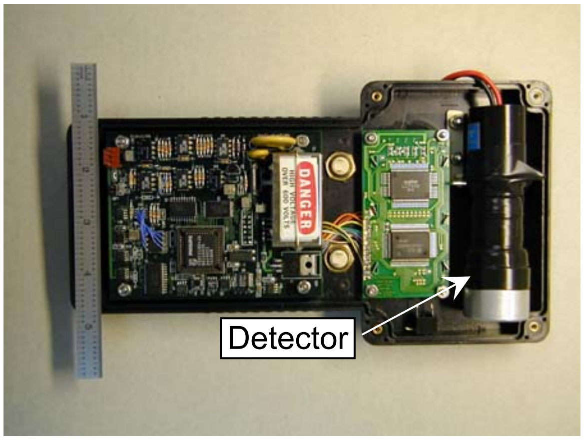


Figure 2b, HotSpotter™, open.



DEVICE OPERATION

The HotSpotter™ is initialized by a series of firmware routines activated when the operator turns on the power with the power switch. These routines include calibration (using a ^{22}Na source), selection of the system gain (0 – 1500 keV or 0 – 3000 keV), acquisition time. The operator answers a series of YES/NO questions via the two pushbuttons mounted on the front panel. Data acquisition begins when the operator starts the sampling mode and continues for the time (30 seconds to two minutes) selected by the operator. At the conclusion of the acquisition interval, the acquired spectrum is searched for peaks. The list of detected peaks is compared to a list stored in the firmware and the results are displayed.

The peak-searching algorithm divides the spectrum into regions whose widths are determined by the resolution as measured during calibration. Full width at half maximum is modeled as

$$FWHM^2 = a \times E + b$$

where E is the gamma ray energy, and the constants a and b are determined from a measured ^{22}Na spectrum.

Starting with the lowest energy of the search region at the threshold channel in the spectrum, the first region is fit with a parabola. If the fit indicates that the parabola is “cup-down”, and that the axis of the parabola is in the region, the region is centered on the axis and the fit is performed again. If a cup-down parabola is found a second time in the region, then the region is also fit with a straight line. If the quadratic fit is sufficiently better than the linear fit (F-test of significance of the quadratic coefficient), then the centroid is recorded. If any previous test fails, the original position of the region is restored; otherwise the centered region is retained. The low energy side of the region is moved by half the width of the region, the new center of the region is calculated, and the width of the new region is set according the model above. The fitting process repeats in this manner until the end of the spectrum is reached.

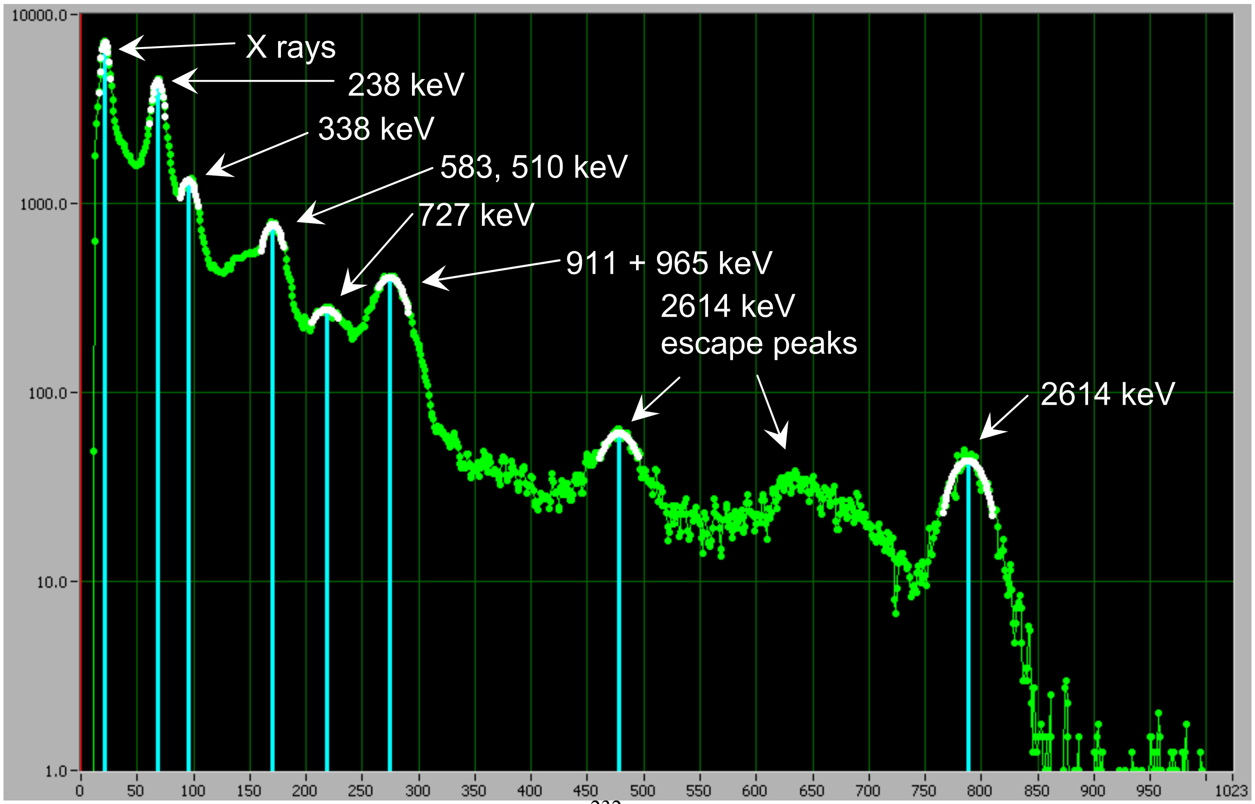


Figure 3, ^{232}Th Spectrum

Figure 3 shows the spectrum obtained from a ^{232}Th source with a 15 mm cube of $CdWO_4$. Note the logarithmic scale. The green represents the data from the HotSpotter™; the white shows the region over which the parabola was fit; the blue line shows the centroid as computed from the parameters of the parabola.

All significant peaks were detected. The resolution of the $CdWO_4$ is insufficient to separate the 911 keV ^{228}Ac gamma ray from the 965 keV emission, and the 510 keV from the 583 keV ^{208}Tl emission. The single escape peak from the 2614 gamma ray was not detected because its proximity to the Compton edge distorts it sufficiently to make the quadratic fit insufficiently better than a linear fit. An improvement in χ^2 of 60% was the criterion for accepting a peak.

STATUS

The HotSpotter™ prototype is essentially complete. Testing to date has demonstrated its ability to detect and identify ^{235}U (in a sample of uranium enriched to 4% ^{235}U), ^{137}Cs, annihilation radiation, and the emissions from ^{22}Na. Work is in progress to decide on a reasonable list of isotopes to store in the firmware's catalog.

Battery life has been found to be approximately 5 hours on a set of four 9V alkaline transistor radio batteries, with the battery supplying the +5VDC regulator being the one to fail first. There is an ongoing effort to find higher energy, lightweight batteries to substitute for the 9-volt batteries.
A viable alternative may be to use a set of AA batteries and DC-DC converters to generate –5 VDC (for the analog amplifiers) and +12 VDC for the high voltage supply.

The instrument can also be improved by the substitution of a mixed-signal microcontroller incorporating the microprocessor, ADC, and additional memory on the same chip. An exemplar is the Cygnal C8051F021 which sports a 12-bit ADC, 8-bit ADC, two 12-bit DACs, comparators, 2 UARTs, 4k bytes of RAM, and 64k bytes of flash program memory. Use of this processor would eliminate the external ADC, memory, and UART, and their support circuits[2]. It is anticipated that one of the DACs would be used to control the high-voltage (thus eliminating a potentiometer), while the other could be used as a pulser to check gain and offset. The 12-bit ADC would be used for acquisition of spectra, while the 8-bit ADC could be used to monitor the various supply voltages.

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[1] Zane W. Bell, J. A. Williams, R. L. Clark, J. K. Mattingly, "Neutron and Photon Detectors for Uranium and Plutonium Applications," Proceedings of the INMM 40th Annual Meeting, Pointe Hilton Resort, Phoenix, AZ, July 25-29, 1999.

[2] Cygnal Integrated Products, 4301 Westbank Dr. Bldg. B, Suite 100, Austin, TX 78746-6564, C8051F021 product data sheet, http://www.cygnal.com/products/C8051F021.htm.

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