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Balloon flight test of a Compton telescope based on scintillators with silicon photomultiplier readouts

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ABSTRACT

We present the results of the first high-altitude balloon flight test of a concept for an advanced Compton telescope making use of modern scintillator materials with silicon photomultiplier (SiPM) readouts. There is a need in the fields of high-energy astronomy and solar physics for new medium-energy gamma-ray (~0.4–10 MeV) detectors capable of making sensitive observations of both line and continuum sources over a wide dynamic range. A fast scintillator-based Compton telescope with SiPM readouts is a promising solution to this instrumentation challenge, since the fast response of the scintillators permits both the rejection of background via time-of-flight (ToF) discrimination and the ability to operate at high count rates. The Solar Compton Telescope (SolCompT) prototype presented here was designed to demonstrate stable performance of this technology under balloon-flight conditions. The SolCompT instrument was a simple two-element Compton telescope, consisting of an approximately one-inch cylindrical stilbene crystal for a scattering detector and a one-inch cubic $LaBr_3$:Ce crystal for a calorimeter detector. Both scintillator detectors were read out by 2×2 arrays of Hamamatsu S11828-3344 MPPC devices. Custom front-end electronics provided optimum signal rise time and linearity, and custom power supplies automatically adjusted the SiPM bias voltage to compensate for temperature-induced gain variations. A tagged calibration source, consisting of ~240 nCi of ^{60}Co embedded in plastic scintillator, was placed in the field of view and provided a known source of gamma rays to measure in flight. The SolCompT balloon payload was launched on 24 August 2014 from Fort Sumner, NM, and spent ~3.75 h at a float altitude of ~123,000 ft. The instrument performed well throughout the flight. After correcting for small (~10%) residual gain variations, we measured an in-flight ToF resolution of ~760 ps (FWHM). Advanced scintillators with SiPM readouts continue to show great promise for future gamma-ray instruments.

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1. Introduction

The fields of high-energy astronomy and solar physics are in need of new instrumentation to make sensitive observations of medium-energy (~0.4–10 MeV) gamma rays from space. In this difficult energy range the instrument of choice for high sensitivity is the Compton telescope, since the coincidence requirement and coarse imaging ability greatly suppress background from cosmic ray interactions in the instrument and spacecraft. The prototypical Compton telescope, and the only one to perform sensitive observations in space, was the COMPTEL instrument on board the Compton Gamma Ray Observatory (CGRO) mission [1]. COMPTEL was composed of two detector layers separated by 1.6 m: a scattering layer (D1), made of up organic liquid scintillator tanks, and a calorimeter layer (D2), made up of inorganic NaI(Tl) scintillator crystals. Scintillation light produced by gamma-ray interactions in the detector volumes (ideally Compton scattering in D1 followed by photoelectric absorption in D2) was recorded by photomultiplier tubes (PMTs), which permitted the location and energy deposit of each interaction to be measured. In addition, the pulse shape of the D1 signals, and the time difference between the D1 and D2 triggers, were recorded. Only events for which the pulse shape indicated a gamma-ray interaction, and the time difference was consistent with a downward-moving scattered photon (~5 ns), were accepted; these pulse-shape discrimination (PSD) and time-of-flight (ToF) discrimination methods proved crucial for rejecting background and achieving a useful *signal-to-noise* ratio.

In the years since the demise of CGRO in 2000, most efforts to advance MeV gamma-ray science have been based on instruments composed of semiconductor detectors with very good ($\lesssim$1%) energy resolution, largely motivated by the goal of studying

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gamma-ray lines produced in cosmic nucleosynthesis and solar flares. The most prominent example in astronomy is the European INTEGRAL mission [2], which features a cryogenically cooled Ge spectrometer array in the SPI instrument [3] and an array of small CdTe detectors in the IBIS instrument [4]. Despite many notable scientific successes at hard X-ray energies, however, INTEGRAL has been unable to significantly improve on COMPTEL's sensitivity at energies $\gtrsim$1 MeV. This is partly because the telescope concept used in both instruments, a coded-aperture imager with massive shielding surrounding the detector arrays, is not optimal for high sensitivity to medium-energy gamma rays, especially in terms of background rejection. Indeed, it has long been recognized that a next-generation Compton telescope would be required to succeed COMPTEL, even before the launch of INTEGRAL, and much work has been devoted to the study of different technological approaches (e.g., [5] and references therein). The most advanced such concept, the Compton Spectrometer and Imager (COSI) balloon instrument [6], also employs cooled Ge as the detector material in order to emphasize sensitivity to lines. Like INTEGRAL, however, Compton telescopes based on semiconductor detector materials suffer from inherent drawbacks that limit their utility for MeV gamma-ray measurements. These include small detector volumes, merely moderate efficiency to gamma ray interactions in the case of Ge, and slow response times that preclude the use of ToF discrimination for event reconstruction and background rejection. We note that, despite its excellent energy and position resolution, the COSI instrument requires an active shield made of heavy inorganic scintillator in order to achieve a low background [6].

In solar physics the most prominent mission dedicated to gamma ray measurements in recent years has been RHESSI [7], which features a Ge spectrometer [8] paired with rotation modulation collimators for spectroscopy and imaging of narrow lines from solar flares. As with INTEGRAL in astronomy, however, the success of RHESSI above $\sim$1 MeV has been limited: despite highly significant scientific contributions from the imaging of hard X-rays and the 2.2 MeV neutron capture line [9], only a handful of gamma-ray line flares have been studied in detail above 2.2 MeV. The most comprehensive set of such flares remains that obtained by the NaI(Tl) gamma-ray spectrometer (GRS) on the Solar Maximum Mission [10]. One reason for this is, once again, the limited stopping power of Ge to MeV gamma rays. Another reason is the slow response time of the semiconductor detectors, which produces pileup and dead time effects during bright flares. Finally, the background in the (unshielded) RHESSI spectrometer is quite high, limiting sensitivity to gamma rays from weaker flares. Indeed, the faintest solar flare known to emit nuclear line radiation was detected by COMPTEL [11], once again demonstrating the superior sensitivity of Compton telescopes in this energy range despite only moderate energy resolution.

The examples of INTEGRAL and RHESSI indicate that sensitive measurements of medium-energy gamma rays from space over a wide dynamic range are best accomplished using large volumes of detectors with good stopping power and fast time response. As exemplified by COMPTEL [1], scintillator materials read out by PMTs have a long history of filling this role, both in astronomy (e.g., [12–16]) and in solar physics (e.g., [17,18]). Scintillator materials have the additional advantages of room temperature operation, radiation hardness, and relatively low cost. When configured as a Compton telescope, the fast time response of scintillators permits the use of the proven ToF discrimination technique for event reconstruction and background rejection. All of these historical advantages have been further strengthened in recent years by the development and commercial availability of newer, higher-performance scintillators. Organic liquids, such as the NE213 used in the COMPTEL D1 layer, are toxic and difficult to handle, while solid plastics have low light output. Recently, however, improved growth techniques [19] have made solid organic crystal scintillators, such as stilbene and p-terphenyl, commercially available in large volumes. These crystals feature improved light output compared to liquids, and retain the ability to distinguish between gamma-ray and neutron interaction signals, due to their differing light decay times, via the PSD technique. Stilbene has been flown in space in the LEND instrument on the Lunar Reconnaissance Orbiter [20]. On the inorganic side, the most promising new scintillator is $LaBr_3$:Ce [21], though other materials such as $CeBr_3$ [22] are of interest as well. Compared to the NaI(Tl) used in the COMPTEL D2 layer, $LaBr_3$:Ce offers greatly improved stopping power, energy resolution ($\lesssim$3% FWHM at 662 keV, vs. $\sim$7%), and time response (26 ns decay time, vs. 230 ns). We note that, since most cosmic gamma-ray lines (e.g., from supernovae and solar flares) are expected to be Doppler broadened by $\sim$2–3%, the energy resolution of these modern advanced scintillators is sufficient for the majority of applications. $LaBr_3$:Ce (hereafter $LaBr_3$) has been the subject of study for a variety of future astrophysics and space science mission concepts (e.g., [23,24]).

All scintillator-based instruments are limited by the mass, volume, and power of the scintillation light readout device. Historically this device has been the PMT, which, despite providing high gain ($\sim 10^6$) and fast time response ($\sim$ns), is fragile, bulky, and requires high voltage ($\sim$1000 V), all of which are drawbacks for a space-based instrument. In addition, it is especially important for a Compton telescope to minimize passive material near the sensitive detector elements, both because such material can become activated by cosmic ray interactions and produce background, and because incident gamma rays that scatter in passive components before interacting in a detector will not be reconstructed properly. For these reasons, fully realizing the potential of advanced scintillators for a next-generation Compton telescope will require replacing PMTs with compact, low-voltage light sensors that retain equivalent quantum efficiency, gain, and timing performance. Fortunately, silicon photomultipliers (SiPMs) are now commercially available that promise to meet this need. Originally developed for high-energy physics applications [25], SiPMs are undergoing rapid development for use in conjunction with various scintillators in nuclear medicine detector systems [26]. SiPMs consist of two-dimensional arrays of small ($\sim$50 μm) avalanche photodiode elements, or "cells," that are operated in limited Geiger mode and read out in parallel. The summed output signal is proportional to the total number of cells that are triggered by the absorption of an optical photon. When coupled to a scintillator, a SiPM will therefore measure the brightness of the optical pulse generated by a gamma-ray interaction. This combination of proportional response with Geiger-mode avalanche operation results in a solid-state light detector with gain ($\sim 10^6$), speed (several ns), and photon detection efficiency ($\sim$30%) nearly equivalent to a PMT. Several SiPMs that have become commercially available in recent years feature quantum efficiency well matched to the blue ($\sim$380–420 nm) scintillation light of materials such as stilbene and $LaBr_3$.

The Space Science Center at the University of New Hampshire (UNH) has for several years been investigating the use of advanced scintillators and SiPMs in instrumentation for high-energy astronomy and solar physics. This work has included the study of $LaBr_3$ for coded-aperture telescopes [27]; the laboratory investigation of SiPM readouts for scintillator spectrometers [28–31]; a successful balloon flight test of a Fast Compton Telescope (FACTEL) prototype with a $LaBr_3$ D2 layer and $\sim$1 ns ToF resolution [32]; the successful balloon flight test of a simple $LaBr_3$/SiPM spectrometer [33]; and a simulation study of the potential sensitivity of an advanced scintillator Compton telescope with SiPM readouts on an Explorer-class space mission [34]. In this paper we describe our most sophisticated experimental effort to date: the balloon flight

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