Determination of Balloon-Altitude Gamma Ray Rates for CREST

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Abstract

Using a small gamma ray detector attached to the TRACER balloon experiment, we measure the atmospheric gamma ray flux in energy ranges between 300 keV and 3 MeV. The instrument was designed to measure the spectrum down to 50 keV, in order to estimate the background in the forthcoming Cosmic Ray Electron Synchrotron Telescope balloon experiment, for which it serves as a pre-prototype. However, electronic noise obscured the lower portion of the spectrum. Results above 300 keV are consistent with previous experiments, with the differential spectrum proportional to $e^{-1.6}$, and we roughly extrapolate that the total count rate above 50 keV would be on the order of ten times the rate above 300 keV.
1 Introduction

This paper describes the preparation of and analysis of data from a small gamma ray detector, which we attached to the TRACER experiment (flown over Antarctica for 10 days in December 2003) in order to determine the gamma ray spectrum in the range of tens of keV to several MeV. This detector was the pre-prototype for a new balloon experiment, the Cosmic Ray Electron Synchrotron Telescope (CREST), which will detect extremely high energy (more than 2 TeV) cosmic ray electrons by detecting the synchrotron radiation they emit as they curve in the earths magnetic field. Aligned photons in the hard X-ray or gamma-ray energy range are assumed to be the signature for electrons, so the Pre-Prototype was constructed to determine the potential background from gamma rays that line up by coincidence.

2 Background

"Cosmic ray" is a term that refers to energetic particles reaching the earth from space, usually from outside the solar system. These particles span an enormous range of energy, from a few MeV up to $10^{20}$ eV (more than a Joule!) and consist of charged particles, gamma ray photons, and neutrinos. It is believed that the charged particles are accelerated to high energy in the shock waves associated with supernovae and their remnants, as high-energy particle emission has indeed been observed in supernovae through observations of x-rays and gamma rays [4]. There have been, and continue to be, many studies to identify the rate of arrival of different cosmic rays of various energies; thus far, however, information on electrons exists only up to about 2 TeV. Because electrons propagating through the galaxy lose energy at a rate proportional to their energy squared [5], extremely high-energy electrons (those beyond 2 TeV) can travel a very limited distance (a few hundred parsecs) before losing most of their energy [3]. If the path length of an electron for a given energy (the distance over which its energy falls from an extremely high level down to that particular energy) is significantly less than the distance to the nearest source of high energy electrons, then no such electrons are detected; thus the energy level at which the electron spectrum declines to zero is directly related to the distance to the nearest cosmic electron source.

A major goal of the CREST experiment is to identify this distance by determining the electron spectrum from 2 to 100 TeV. Because the electrons in this energy range are so rare, and because their direct detection would require a prohibitively heavy detector for a balloon experiment, CREST will use a novel method of detection. Instead of directly detecting electrons, it will detect the synchrotron radiation they emit (at x-ray or gamma-ray energies, due to the high energies of the electrons) as they curve in the earths atmosphere. The photons are emitted tangentially to the electrons path, so a line of three or more photons arriving at almost exactly the same time (within 2 nanoseconds) signals an electron [6]. The detector itself will be 2m by 2m, composed of 5 cm by 5 cm Bismuth Germanium Oxide (BGO)crystals, each connected to a PMT. The energy of each photon is absorbed by the BGO crystals, resulting in scintillation light that is converted into
electrical signals in the PMTs, from which the data is read out and stored in the experiment's computer system. This photon energy allows an estimate of the electron's original energy in turn; from simulations, there is a reasonably good correlation between average photon energy and the energy of the originating electron, allowing the determination of the electron energy within a factor of two [6], which is sufficient to estimate the electron energy spectrum with some accuracy if sufficiently many events are detected.

Of course, a key background signal that must be corrected for is the possibility of photons from other sources striking the detector simultaneously by coincidence. This is highly unlikely, but cosmic ray electrons with such high energies are extremely rare as well—if, indeed, they exist at all. Although initial studies indicated that this background will be on the order of only one event in one hundred days [6], the background rate of cosmic gamma rays in the upper atmosphere (where CREST would be flown) was in fact not known as accurately as might be expected.

3 Instrument Description and Assembly

The Pre-Prototype was conceived as a means of addressing this gap in knowledge. It consists of a crystal, a photomultiplier tube (PMT), an amplifier, a multi-channel analyzer (MCA), and a simple computer system for data storage. The crystal is BGO, the same material that is proposed for CREST itself. BGO has a density of 7.13 g/cm³, and is composed of 67.1% Bismuth, 17.4% Germanium, and 15.1% Oxygen by weight, with a radiation length of 1.11 cm [2]. The crystal has a thickness of 1 cm (comparable to the radiation length) and radius of 2.54 cm. Gamma rays are detected by the crystal and converted to electrical signals by the PMT, whose output amplitude can be adjusted by changing one of the voltage inputs. The signal is then amplified and passed to the MCA, whose function is to store the frequency of data in each of 4096 channels (corresponding to PMT output voltage). Every ten minutes, the MCA memory is transferred to a simple 486 processor running a minimal version of Windows. The system can have a monitor, keyboard, and mouse attached to insure that it is functioning correctly, and have an external hard drive and disk drive attached for software modification.

There are several different types of software included on the project’s computer system. The software originally supplied with the MCA can be used with an external hard drive, and provides a good visual image of the spectrum being processed by the system. However, it is not intended for long-term data taking, so a separate program (using C++ tools provided by the company that produced the MCA) was written at the University of Michigan; it records 10-minute blocks of data as C++ structures in binary format. It also sets a watchdog timer which reboots the system unless reset every 30 seconds; this allows the software to restart itself in the event of a crash.

The MCA and computer system were initially assembled and connected at the University of Michigan, then subsequently brought to the University of Chicago for connection to the detector, fine-tuning, calibration, and testing. This work included some wiring within the pressure-sealed can containing the MCA and computer system, wiring between the can, the detector, and power systems, and modifications to the computer software.
Although the wiring inside the pressure-sealed can was almost entirely completed at the University of Michigan, the author was primarily responsible for external wiring. This included wires for a 28 volt power supply from the TRACER instruments batteries, as well as a 12V line going from a voltage-converter inside the can (which produces 12V for the computer system) to the PMT. The PMT also requires a separate, adjustable supply to change the amplitude of its output, which was produced by an engineer at the University of Chicago.

4 Instrument Testing

The first task in testing the assembled system was to determine the appropriate calibration for the PMT output. For this purpose, we used a piece of fabric from a gas lamp (called “the sock”), which contains traces of Thorium 232. The thorium has several notable lines in the energy range investigated by the pre-prototype (at 70 keV, 240 keV, 583 keV, three in the 911-969 keV range, and one at 2615 keV), enabling the linear ratio between gamma-ray energy and MCA channel to be checked and calibration to be determined. However, the precise calibration varies over time, due to small changes in the input voltage and other factors (see next paragraph), so a piece of the “sock” was attached to the crystal during flight to provide in-flight calibration. The second phase of testing was to fully seal the can and allow it to run overnight as it would in flight, and make sure that it continued to record data properly. Setup for these tests revealed one problem with the system: although it restarts in the event of a crash, if it crashes or is shut down during startup, it reboots in safe mode and does not begin the flight software or watchdog timer. In order to counteract this problem in the event it occurs (which cannot be determined from the ground), we decided that the power system for the instrument would be cycled several times during flight to insure a clean startup.

The final testing phase was pressure testing, using a bell jar and vacuum pump to reduce the pressure to roughly the pressure at the level the balloon was flown at (a few millimeters of mercury). Although the can was well sealed, and the system continued to function, we observed that the channel-to-energy ratio decreased by about 20% during the first few hours of reduced pressure. This necessitated further tests, which determined that the new ratio remained constant after these few hours (meaning that, with in-flight calibration, good data can still be recorded). There was insufficient time to determine the cause, although we were able to determine that there was no pressure loss within the can, meaning that the MCA, amplifier, and computer were unlikely to be the culprit. It may be that the external battery for the adjustable PMT voltage was affected by the decreased pressure, but if so there would most likely be lasting effects on the output voltage after it was removed from pressure, which is not the case. The most likely hypothesis is that there is an air bubble under the crystal whose expansion in low-pressure affects the signal gain between the crystal and PMT. Interestingly, this effect was much less pronounced during flight, suggesting perhaps that the effects of the air bubble were reduced as a result of repeated vacuum tests.
Figure 1: Differential spectrum from sum of all full-altitude runs, prior to background subtraction. The visible peak from the in-flight calibration Thorium-232 source is indicated.

5 Data Recovery and Analysis

The data taken in Antarctica corresponds to a few ten-minute pre-light test runs, including final runs after installation of the pre-prototype on TRACER, and roughly eighty runs around launch time (evenly divided between pre-launch and during the ascent). Near the end of the ascent, the pre-prototype was shut down briefly, and restarted roughly two hours later. About one thousand data runs at full balloon altitude were taken. Each run corresponds to ten minutes of real time, of which 2-3 minutes is live time. The live time is significantly smaller than expected due to a large amount of unexpected electronic noise in the region of the spectrum below 300 keV; it is nevertheless sufficient to provide a large quantity of information in regions above this energy.

Once the data were recovered, we wrote C++ programs to display and analyze the data. These included programs to display counts per channel, to identify specific runs with minimal electronic noise, to calibrate the energy scale (see below), to integrate the total signal above a given energy, and to compare multiple runs and find the difference between them. This last program is useful for background subtraction, and provided a slight programming challenge because, after calibration, data points corresponding to specific channels in different data sets no longer correspond to the same energy value.

The most prominent feature of the differential energy spectrum at full altitude (Fig. 1) is a very large peak below energies of about 300 keV. This does not appear in final test
runs after the instrument was attached to TRACER, but does appear on runs in the hours preceding launch, and remains throughout the flight. Thus it can be concluded that the peak is most likely electronic noise caused by some component (most likely communications) of the TRACER instrument. Since the ranges that have the potential to produce a background signal in CREST include photons of energies of 50 keV and up, the presence of this electronic noise detracts from the available data; although some effort can be made to extrapolate down from 300 keV to 50 keV (see below) it is impossible to extrapolate over nearly an order of magnitude with significant confidence.

The thorium source attached to the detector in flight for calibration has four major peaks visible on the setup for the pre-prototype; the most important for this analysis are the 583 keV peaks and the three peaks in the 911-969 keV range (which the detector has insufficient resolution to distinguish). Only these two features are visible after noise is introduced, and only the last one is visible at full altitude when this calibration signal is small compared to total signal. This actually represents a good success, given that the correct amount of signal from the calibration source could only be roughly estimated; the calibration signal is small compared to the physics data, but still distinct enough to be used for calibration. Two peaks might have been preferable for more precise calibration, as with only one peak available the only possible calibration is to assume that channel 0 corresponds to 0 energy and do a simple linear fit. Prior to the appearance of noise, the 911-969 peak corresponded to channel 1600, whereas it corresponds to channel 1350 afterwards, and to channel 1300 at full flight altitude. The signal as a function of channel is simply scaled by this amount to produce plots of the differential energy spectrum. This calibration results in good correlation of the runs at ground level before and after the introduction of noise (outside of the noise range, of course), and that the signals are nearly identical above roughly 800 keV.

After calibration, we have produced plots of the integral rate by simply summing the total signal above each energy. In order to find only signals due to actual gamma-ray presence at balloon altitude, we take the signal immediately prior to launch (when electronic noise has been introduced) as the background, and subtract it from the integral rate at balloon altitude. This plot of background-subtracted integral rate for the sum of all runs at full altitude (Fig. 2) reveals a signal of about 30 photons per second at the lowest energy at which it is reliable (i.e. about 300 keV).

Using individual runs from the ascent and time-altitude data from the TRACER experiment, we have constructed a plot of gamma ray signal as a function of altitude (Fig. 3). The plot has lines for the integral rate above 400 keV, 800 keV, 1400 keV, and 2000 keV. It reveals that the maximum signal occurs at roughly 60,000 feet, consistent with generally understood results for atmospheric cosmic ray signals—the peak is known as the Pfitzer maximum. Above this peak value, there is too little atmosphere to produce many interactions between atmosphere and cosmic rays (which form a significant source for the gamma rays that are detected in the atmosphere), whereas below this altitude the atmospheric overburden is thick enough to significantly reduce the number of cosmic rays available for such interactions.
Figure 2: Background-subtracted integral spectrum for all full-altitude runs.

Figure 3: Integral spectrum above 400, 800, 1400, and 2000 keV for runs during the ascent. Note Pfutzer maximum around 60,000 feet.
Figure 4: Background-subtracted integral spectrum for all full-altitude runs. Power law dependence of region between 300 and 600 keV, and between 600 and 900 keV, is indicated.

6 Simulation of the Detector

From previous experiments (e.g. [7]), we expect that the spectrum of balloon altitude gamma rays should have a power law dependence on energy. In fact, a log-log plot of the energy-calibrated background-subtracted integral spectrum for the full-altitude runs (Fig. 4) reveals that there are three regions above the energy of 300 keV: the region from roughly 300 to 600 keV goes with E\(^{-1.14}\), the region from 600 to 900 keV goes with E\(^{-0.83}\), and the region beyond this does not fit a power law spectrum at all. In order to better understand these regions, we consider the effect of detector performance on the actual energy spectrum.

Our first approach was to use experimentally-derived tables of photon-interaction cross sections for Bismuth Germanium Oxide [1], along with the assumption that a photon is either completely absorbed in the detector or does not interact at all, to create a plot of detector efficiency as a function of energy (Fig. 5). The efficiency depends on how much detector thickness the photon is assumed to pass through, with the horizontal (greatest possible thickness) and vertical (least possible thickness) limits displayed on the plot. From here, the differential spectrum can be adjusted in the vertical and horizontal limits (e.g., see Fig.10), giving a range of reasonable values for the true spectrum. This corrected spectrum still has all the features of the original (albeit with specific slope values changed), so this method does not explain the existence of three separate regions in the spectrum.
Figure 5: Efficiency of the detector, assuming that incoming gammas are either fully absorbed or undetected, for two limits: photons pass through horizontally (5.08 cm of BGO) or photons pass through vertically (1 cm of BGO).

To obtain a better understanding of the spectrum, it is necessary to account for the possibility that only part of the energy of a gamma ray will be absorbed in BGO; for this purpose, we used a full GEANT4 simulation of the detector. These simulations reveal that the energy is indeed partially absorbed much of the time; for example, 2.5 MeV photons passing vertically through the detector leave only part of their energy more often than they are fully absorbed.

Initially, we used the energy spectrum estimate given by Schönfelder et al. [7], that the differential spectrum of atmospheric gammas at balloon altitude goes with $E^{-1.7}$, as a starting point for simulations. Plots of the spectrum initially simulated, and the energy spectrum “detected” in the simulation, were created for the vertical (Fig. 6) and horizontal (Fig. 7) cases. It is clear that the assumption of photons arriving solely in the horizontal direction, with is spectrum in the region of 300 to 900 keV going as $E^{-0.98}$, represents the experimental data significantly better than assuming purely vertical gammas. However, the simulated data above 1 MeV do not match well with the experimental data, and the two different regions of energy dependence below 900 keV are not reproduced either.
Figure 6: Simulated "original" and "detected" integral spectra, assuming that all photons pass through the detector vertically.

Figure 7: Simulated "original" and "detected" integral spectra, assuming that all photons pass through the detector horizontally.
Figure 8: Simulated angular dependence, produced using a piecewise approximation of the angular dependence obtained by Schönfelder. Oscillations are due to low simulated statistics. Note that the greatest rate is from below the experiment, because most radiation is from secondary production and there is vastly more atmosphere below the experiment than above. Peak at 120 degrees is due to the horizon.

Rather than assuming that all particles come from the same direction, we further refined the simulations by introducing the angular dependence observed by Schönfelder et al. (Fig. 8). After some fine-tuning of the energy dependence, the result of this simulation (Fig. 9) fits with the experimental data much better; two regions between 300 and 900 keV with approximately the correct energy dependence. The simulation still does not account for the shape of the spectrum above 900 keV; however, this feature is unlikely to be due to a feature of the detector, since an increasing and then decreasing power law dependence is not consistent with the trend of decreasing detector efficiency throughout the energy range of interest.

7 Conclusions

We flew a small gamma ray detector, the Pre-Prototype for the CREST experiment, attached to the TRACER balloon instrument, and measured the photon energy spectrum from 300 keV to 3 MeV, in order to estimate backgrounds in CREST. We intended to measure the spectrum between 50 keV and 300 keV as well, but these data were lost to electronic noise.
Figure 9: Simulated "original" and "detected" integral spectra, assuming incoming photons have an angular dependence as obtained by Schönfelder.

From simulations we have that the best fit differential energy spectrum in the region between 300 and 900 keV is proportional to $E^{-1.6}$, quite close to the value obtained by Schönfelder. The energy dependence of the differential spectrum above 900 keV does not fit with that found by Schönfelder. Although he does cite the existence of a "hump" in the primary spectrum starting around 1 MeV, this does not appear in the total spectrum, which is dominated by secondary particles; thus the "hump" cannot constitute a satisfactory explanation and the spectrum at these energies remains unexplained.

It is also useful to determine the total flux we found with that of Schönfelder. Using rough estimates for the appropriate geometric factor for our detector, we used the vertical and horizontal limits on detector efficiency to find the rough value of flux as a function of energy. The resulting flux is roughly a factor of 2 greater than the power law fit produced by Schönfelder (Fig. 10). This discrepancy is easily accounted for by the fact that the flights on which his fit is based were conducted in Texas, where a higher geomagnetic cutoff reduced the number of primaries and thus the total flux, rather than in Antarctica.

We made a rough extrapolation of the integral rate at 50 keV from three different power laws: that obtained from the vertical limit of detector efficiency, that obtained from the horizontal limit, and that obtained from the simulation using Schönfelder’s angular dependence. In all three cases, the result gave a rate of 150-200 counts per second. Since this extrapolation is over an entire order of magnitude, it is extremely rough at best, but it is reasonable to conclude that the count rate would indeed be on the order of a few
Figure 10: Comparison of Schönfelder's linear fit to the flux as a function of energy at balloon altitude to the adjusted spectrum (vertical and horizontal limits shown) found in this experiment. Given that the count rate at 300 keV is 30 counts per second, we expect the counts above 50 keV to be about an order of magnitude larger than those above 300 keV.
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References


