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Prototype TIGRE Compton Gamma-Ray Balloon-Borne Telescope

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Abstract

A prototype balloon-borne telescope is being constructed for gamma-ray observations in the MeV energy range. The Tracking and Imaging Gamma Ray Instrument (TIGRE) uses multi-layers of thin silicon detectors to track and measure the energy losses of Compton recoil electrons. When combined with the direction and energy of the Compton scattered gamma ray a unique incident direction for each photon event is determined. This facilitates background rejection, improved sensitivity, and image reconstruction. The converter/tracker also serves as an electron-positron pair detector for gamma rays up to 100 MeV. The initial continental U.S. flight will be used to determine the sub-orbital atmospheric backgrounds and search for polarized gamma emission for the Crab pulsar. Longer southern hemisphere flights with an enhanced instrument will map out the ^{26}Al emissions from the galactic center region.

Key words: gamma-ray astronomy, Compton telescope, electron tracking
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1. Introduction

Improved medium-energy gamma ray instruments are needed for future investigations of nuclear line emissions from supernovae and the Milky Way and continuum emissions from pulsars and AGNs, including polarization. Significant improvements in background-limited sensitivity can be achieved with the careful balance of new detector technologies and new imaging techniques. The development and flight of the TIGRE Compton telescope as part of a mid-latitude "long duration" or "ultra long duration" balloon observation program is an essential step for TIGRE to be considered a candidate for a future Advanced Compton Telescope (ACT) space mission.

2. Electron Recoil Tracking with Silicon Detectors

Compton telescopes use two gamma-ray detector elements in coincidence; ideally, the first is a low-Z converter to favor Compton scattering over photoelectric absorption and the second is a high-Z calorimeter to completely absorb the scattered photon. Past Compton telescopes (Schönfelder et al. 1973, Herzo et al. 1975, Zych et. al. 1983, Schönfelder et. al. 1984) and some newer concepts using germanium strip detectors (Kroeger et al. 1995,

Boggs 1998), thick silicon detectors (Kurfess et al. 2000), and liquid xenon time projection chambers (Aprile et al. 1993) can only determine the incident direction of each photon to an event circle superimposed on the sky with radius θ, calculated from the Compton scatter formula. This event circle is shown in Figure 1. The *azmuthal* uncertainty is due to the lack of knowledge of the recoil electron's direction. Event circles from background gamma rays incident at large angles with respect to the source direction can also intersect the source direction and contribute to the source background. When several sources are within the telescope's field-of-view, events from one source can contribute to the image of the other(s). These problems can be substantially reduced with recoil electron tracking.

The TIGRE instrument (Tümer et al. 1995, O'Neill et al. 1995), features multilayers of silicon strip detectors as both the Compton converter and recoil electron tracker. This concept is similar to the MEGA instrument of Kanbach et al. (2003). Double-sided silicon strip detectors provide sub millimeter positions and high-resolution energy-loss measurements as the recoil electron is tracked through successive silicon layers. As a tracker, recoil electrons can still be tracked at gamma-ray energies below 1 MeV (O'Neill et al. 1995). For example, at

0.511 MeV, 9% are tracked events. TIGRE still operates as a conventional Compton telescope when the electron originates and stops in the same layer. Monte Carlo simulations show that the percentage of tracked events increases to 57, 82, and 94% for 1, 2, and 6 MeV gamma rays.

Previously, Compton and pair telescopes used the time-of-flight (TOF) of the scattered gamma rays or pair particles between two scintillator arrays to determine the direction-of-motion and discriminate against unwanted background. This required a large converter-calorimeter separation and small FOV and corresponding lower efficiency. With silicon strip detectors the track record of energy loss and position in each silicon layer the electron traverses is used to determine the direction-of-motion (DOM) parameter for each track (O'Neill et al. 1995). This parameter compares the expected energy losses and angle changes with the measured values for electrons stopping in two or more consecutive silicon layers. For two-layer tracks only the energy losses are used. Typically, the beginning of a recoil electron track is assigned incorrectly less than 10% of the time.

Doppler broadening occurs in Compton interactions due to the nonzero momentum of the bound atomic electrons of the converter material. This shows up as an energy fluctuation in the Compton scattered gamma ray. TIGRE measures the full energy of both the recoil electron and the scattered gamma so that the total event energy is unaffected. However, this effect causes an error in the calculated Compton scatter angle, θ, affecting the angular resolution of the telescope. A Compton telescope's angular resolution is defined in terms of the *angular resolution measure* (ARM), which is the difference between the true photon scatter angle and the scatter angle reconstructed from the Compton scatter formula and the positional information.

Figure 2 shows our calculated angular resolutions, including the contribution from Doppler broadening, for 60° Compton scatters, midway between the 30° to 90° TIGRE range. TIGRE's angular resolution is 2^O (1-σ) at 1 MeV. The largest contribution to this value is the spatial and energy resolutions of the CsI detectors. With calorimeter resolutions of a few mm and a few keV this can be reduced to 0.3^O (1-σ). The Doppler broadening contribution in silicon is 0.4^O (1-σ) at 1 MeV.

Doppler broadening represents a serious limitation to any future high resolution Compton telescope. Thick converters with multiple Compton interactions and high-Z converters both work to increase this effect. TIGRE uses single interactions in silicon so

that the effect of Doppler broadening is minimized. An Advanced Compton Telescope based on the TIGRE concept with a silicon converter/tracker and a high-resolution Ge or CZT calorimeter will be able to work at the Doppler broadening limit.

Intermediate high-energy (10-100 MeV) gamma-ray measurements are needed to complement the major new discoveries expected above 100 MeV with GLAST. TIGRE is an excellent gamma-ray pair telescope above 10 MeV. Figure 3 presents the expected pair angular resolutions for TIGRE and GLAST from 10 to 100 MeV. The TIGRE instrument with an area of about 1600 cm^2 will be about a factor of two more sensitive than GLAST below 100 MeV. Its angular resolutions at 10 and 100 MeV are 6° and 0.8^O (1-σ) , respectively.

Compton telescopes are natural gamma-ray polarimeters, making use of the sensitivity of the Klein-Nishina cross section for large angle Compton scatter events. TIGRE's well-type calorimeter design makes it well suited as a gamma-ray polarimeter for energies below 2 MeV. The polarimetry properties of the TIGRE Compton telescope have been previously described in Akyüz et al. (1995). A conventional balloon observation with the full-area TIGRE instrument will be able to detect polarized gamma rays at the 10-20% fractional polarization level for source fluxes comparable to the Crab flux.

3. Prototype Instrument

Each silicon double-sided detector (Micron Semiconductor Ltd) is 10-cm x 10-cm x 300-μm thick. Each side has 128 orthogonal strips with a pitch of 0.758 mm. An aluminum metalization layer above each strip provides a 1000 pF AC coupling capacitance. The detectors are fully depleted at a bias voltage of 40 volts where the single detector leakage current is typically 2 μA. An 80-MΩ polyscin bias resistor is fabricated on the chip at the end of each strip. A single guard ring surrounds the bias ring on each side. Preliminary measurements of the energy resolution for a single detector with 122 keV gammas from ^{57}Co gave 4.6 keV (1-σ) (O'Neill et. al. 2003).

Two 128-channel TAA1 ASICs (IDE AS, Oslo) are used to read out the strips on each detector board. Each chip provides a prompt asynchronous signal-above-threshold trigger. Triggers from the junction and ohmic sides (x and y strips) are combined on each board. An optional mode requires triggers from adjacent layers to ensure that only tracked electron events are recorded. Each pair of detector ASICs is read out serially with a single VME ADC channel.

The entire detector readout is accomplished in the time it takes to clock through the 256 channels.

The prototype instrument has a mosaic of four detector boards stacked 16 layers deep (16,384 channels). The initial spacing between layers is 1.52 cm.

TIGRE currently uses 1-cm x 1-cm x 3.5-cm long CsI (Tl) crystals (Hilgar Ltd.), individually wrapped with multilayers of Teflon tape and bonded to 1-cm^2 photodiodes (Hamamatsu S-3590-03) to measure the energy and direction of the scattered gamma ray. Single crystal spectra connected to discrete electronics consistently gave resolutions of 5% FWHM at 662 keV. Arrays consisting of 256 crystals are read out using the same TAA1 ASICs. Initially, the prototype instrument will use five arrays on the sides and bottom of the 64-detector silicon converter/tracker stack. The triggers for all the crystals are combined to produce the calorimeter trigger. "Good-event" triggers require a coincidence in the converter/tracker and calorimeter triggers with no signal from the plastic scintillator charged particle shield that encloses the silicon and CsI detectors.

The silicon converter/tracker stack and five CsI(Tl)-PD arrays have been configured to fit within the existing dimensions of a previous balloon-borne thin-walled pressure vessel. We have added eight existing NaI(Tl) position-sensitive bar-type scintillators below the silicon stack and bottom CsI(Tl) array. They will stop the higher energy gamma-ray pair particles and measure the positions and energies of these stopping electrons and/or positrons. This extends the pair energy range to 100 MeV.

The prototype instrument design allows for considerable expansion in the size of the silicon converter/tracker. The number of layers can easily be expanded from 16 to 32 deep. Similarly, when future funding permits, four silicon stacks can be enclosed within the charged particle shield and pressure vessel for a total sensitive area of 1600 cm^2. This represents the *full-area* TIGRE instrument. Additional CsI(TL) arrays will be required, including arrays between the individual silicon converter/tracker stacks. Two stacks would share these arrays.

4. Instrument Simulation

A realistic mass model for TIGRE has been simulated to determine its relevant performance parameters. The Los Alamos MCNP (Monte Carlo Neutron Photon) code was used. Thirty-two silicon layers with an area of 1600 cm^2 were used, with CsI 3.5 cm thick on five sides. The energy and spatial resolutions for the converter/tracker were taken to be 3 keV (1-σ) and 0.75 mm, respectively. Thresholds of 30 keV, 100 keV, and 100 keV for the silicon, CsI, and charged particle shield were used. The standard scaleable resolution (5% at 662 keV) for the CsI(Tl) was used. The atmospheric gamma-ray fluxes were taken from our previous balloon flight results (Akyüz et al. 1997) and modeled over the full 0-180° zenith angle range. Source fluxes were simulated using a Crab-like E^{-2} power law spectrum. The smaller cosmic diffuse gamma emission was not included in the downward background at 3 mbars.

The absolute on-axis detection efficiency for the TIGRE mass model is 5%, giving an effective area of 80 cm^2 at 1 MeV. This can be increased with additional silicon layers (up to 64) and thicker CsI below the silicon. At 1 MeV the energy resolution is 20 keV (1-σ). This can be reduced to <5 keV with a Ge or CZT calorimeter.

A series of data cuts have been developed to eliminate the gamma-ray background while retaining the source events. The large contribution by the upward moving and horizon background is of particular concern. Accepting events with Compton scatter angles greater than 35° drastically reduces the number of background events that interact in the calorimeter first without significantly affecting the on-axis efficiency. Accepting events with incident directions within the 70° half-angle instrument FOV further reduces the background. The use of the DOM parameter is implicit in the FOV cut. Hence, these two cuts (scatter angle and FOV) reduce the amount of background and act as an effective TOF cut. Over 90% of the gamma rays originating outside the FOV are eliminated.

MCNP was also used to simulate the response of the TIGRE instrument to the known atmospheric neutron background measured with a double scatter telescope (Ait-Ouamer et al. 1988). Neutrons are slowed and captured in the material of the telescope. Fast neutrons can have direct reactions. Both prompt and delayed gamma emissions are produced. The most prominent prompt gamma-ray lines are seen at 1.81 MeV (^{27}Al(n,pn)γ) and 0.511 MeV. There are lesser lines from aluminum at 0.84, 1.01, and 2.02 MeV. It is important to measure the neutron-induced background during an actual balloon flight.

We use the maximum likelihood (ML) analysis method to determine the TIGRE instrument sensitivity to gamma ray sources during a balloon flight observation. A model that includes the point-spread-function (PSF) for a discrete source and the

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simulated gamma background is compared to a model that just includes the background (null hypothesis). A minimal one-dimensional PSF with radial symmetry is determined from the reconstructed incident direction using electron tracking. The likelihood ratio test and the resulting test statistic, T_S, are used to find the statistical significant of the observation. The significance of a source detection at a specific position is given by $\sqrt{T_S}$ σ (Mattox et al. 1996). According to Wilks' theorem, T_S is distributed as χ^2 under the null hypothesis (Wilks 1938).

In the simulation the entire mass model was contained within a sphere with a radius of 70 cm, projecting an area of 15.4×10^3 cm^2 in all directions. During a 7-hour exposure at 3 mbars, 3.24×10^8 background and 1×10^6 Crab source photons will be incident on the TIGRE mass model in the 1-30 MeV energy range. Of these, 2×10^3 source and 1.5×10^5 background events will be detected. Only 20 million background gammas were simulated and the results were scaled accordingly. The results show that a Crab-like source at zenith will be detected with a 9.6 sigma statistical significant while the same source at 30° off-axis will be detected at 7.5 sigma (Akyüz et al. 2003). When the electron tracking information is disregarded the corresponding sigma-values are 3.8 and 3.3. For the non-tracking case, the source PSF is generated by first smearing the source directions uniformly along the entire event rings.

The improvement of a factor of ~2.5 in sensitivity with recoil electron tracking reduces the required exposure time to detect continuum sources by a factor of 6. The 9.6-σ value translates to a 3-σ integral sensitivity of 7×10^{-4} ph cm^{-2} s^{-1} over the energy range of 1-30 MeV. The 7-hour exposure used here will locate the Crab to within a 4° (68%) error circle. The prototype instrument described in this report only has one-fourth the area and one-half the thickness of silicon of the *full-area* telescope.

When Ultra Long Duration Balloon (ULDB) flights are realized with 100-day observations (700 hr or ~2.5×10^6 s exposures to individual sources) the sensitivity is improved by a factor of ten. Mid-latitude Long Duration Balloon (LDB) flights of ~10 days will improve our sensitivity by a factor of three. These are possible if some daily altitude variation is acceptable. Improvement in the angular resolution from 2^O to 0.4^O (Doppler limit) will improve the sensitivity by another factor of 2.2. This can be realized with improved calorimeter materials. The broad line sensitivity at 1.8 MeV (^{26}Al) is 1.1×10^{-4} ph cm^{-2} s^{-1} for a 7-hour exposure. For a 100-day observation with TIGRE with an improved calorimeter this reduced to 1.4×10^{-6} ph cm^{-2} s^{-1}.

4. Conclusion

The proposed balloon flight with the prototype instrument is needed to verify the backgrounds and performance parameters. Improved calorimeter materials, for angular resolutions at the Doppler limit, and longer exposures will increase TIGRE's overall sensitivity. ML calculations with a realistic two-dimensional (θ and ψ in Figure 1) PSF, made possible with electron tracking, should demonstrate that TIGRE's sensitivity could be increased further. This work is in progress.

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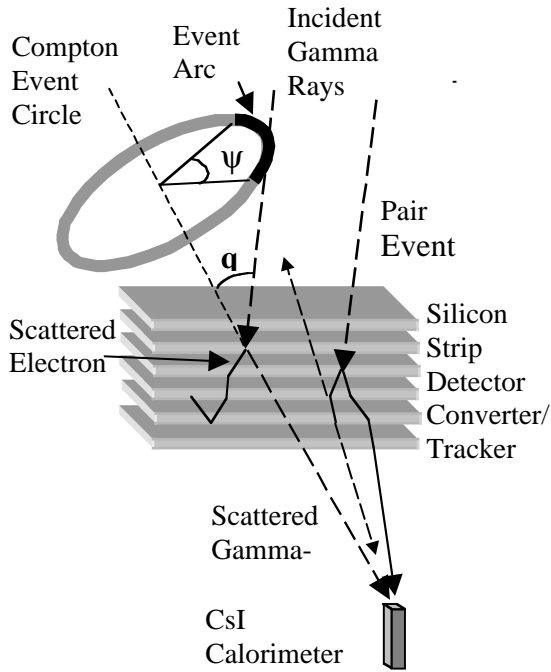
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Figure 1 Compton and pair events in the silicon converter/tracker
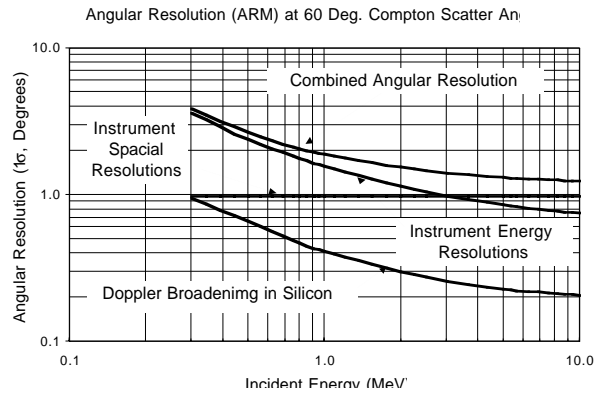

Figure 2. Angular resolution of the TIGRE prototype instrument including Doppler Broadening for 60° scatter angles in silicon.
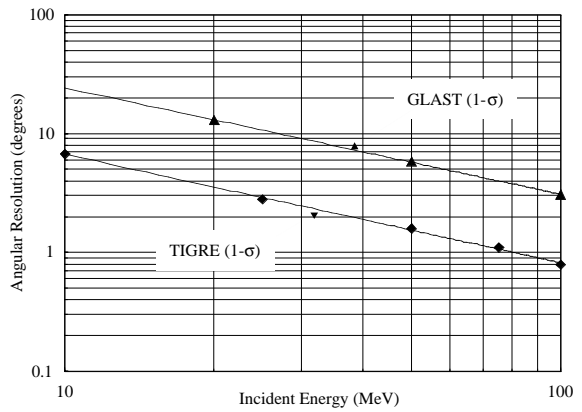

Figure 3. Comparison of Pair Angular Resolutions of TIGRE and GLAST