A Tracking and Imaging Gamma-Ray Telescope (TIGRE) for energies of 0.3 to 100 MeV

D. Bhattacharya[1], D.D. Dixon[1], V. Kong[1], T.J. O'Neill[1], R.S. White[1], A.D. Zych[1], J. Ryan[2], M. McConnell[2], J. Macri[2], J. Samimi[3], A. Akyuz[4], W.A. Mahoney[5], L.S. Varnell[5]

[1]IGPP, University of California, Riverside, CA 92521, USA
[2]Space Science Center, University of New Hampshire, Durham, NH 03824, USA
[3]Dept. of Physics, Sharif University of Technology, Tehran, Iran
[4]Dept. of Physics, Cukurova University, Adana, Turkey
[5]Jet Propulsion Laboratory, 169-327, 4800 Oak Grove Drive, Pasadena, CA 91109

Abstract

TIGRE is an advanced telescope for γ-ray astronomy with a few arcmin resolution. From 0.3 to 10 MeV it is a Compton telescope. Above 1 MeV, its multi-layers of double sided silicon strip detectors allow for Compton recoil electron tracking and the unique determination for incident photon direction. From 10 to 100 MeV the tracking feature is utilized for γ-ray pair event reconstruction. Here we present TIGRE energy and angular resolutions, electron tracking measurements and electronics readout system. The scientific objectives of TIGRE on a long duration balloon flight or space mission will include high resolution imaging of the diffuse ^{26}Al and the annihilation radiation, and also the search for other nuclear lines. Other objectives include obtaining AGN and pulsar spectra and mapping of the Galactic continuum diffuse emission.

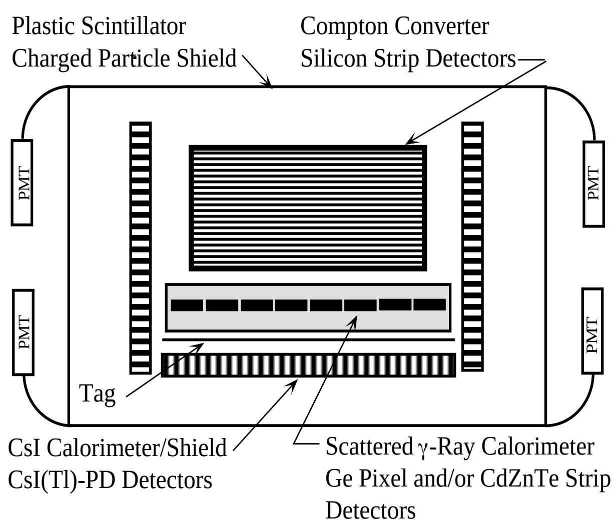

Figure 1: TIGRE Instrument.

Instrument Description: The TIGRE instrument, shown in Fig. 1, features multilayers of silicon strip detectors (SSD) as both the Compton converter and recoil electron tracker. Double-sided SSDs provide submillimeter x and y spatial resolutions as the recoil electron is tracked through successive layers until it is fully absorbed. Position sensitive Ge and CdZnTe detectors are used as a calorimeter for the scattered photons and electron-positron pairs. TIGRE consists of 32 layers of Si strip detectors each with sixteen 10 cm$\times$ 10 cm $\times$ 300 μm detectors with a spatial resolution of 0.75 mm. The Ge calorimeter below the Si array consist of 64 planar pixel detectors, each 5 cm $\times$5 cm $\times$ 2 cm thick. The pixel size for the Ge is 3 mm. Alternatively, thick CdZnTe strip detectors can be used. CsI(Tl)-Photodiode detector arrays on the bottom and sides serve as a low energy γ-ray shield. This is important at energies below 1 MeV where up-down discrimination of γ-rays cannot be determined. The shield also serves as a Compton suppressor below the Ge array for γ-rays leaving the Ge. The side CsI(Tl) arrays serve also as a calorimeter for large scatter angle events. This is particularly important for polarization measurements below about 2 MeV. The individual CsI(Tl) array elements have dimensions of 1 $cm^2 \times$ 3.5 cm. A particle anticoincidence plastic scintillator surrounds the entire sensitive material.

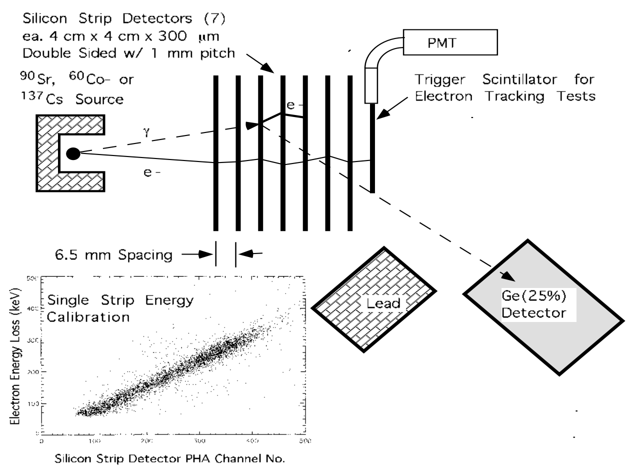

Figure 2: The laboratory setup used for the silicon germanium double scatter experiment.

For γ-ray pair events both the energy losses and positions are measured in each Si layer as these particles are tracked through the array. The incident γ-ray direction is reconstructed from the tracking information near the vertex of the event. It's energy is estimated from the total energy losses in the telescope. Tracking the recoil electron will restrict the incident γ-ray direction to a small arc on the event circle with length equal to the azimuthal projection of the Coulomb scatter angle at the beginning of the track. The projected scatter angle for 1 MeV electrons in 300 μm of Si is $\sim 18°$ or $\sim \frac{1}{20}$th of the event circle. This reduces the background events proportionally and increases the telescope's sensitivity.

Silicon Strip Detector Measurements: We have used a ^{90}Sr beta source and a stack of 7 silicon strip detectors 300 μm thick (Fig. 2) to measure the electron multiple scattering. A least squares method was adopted to obtain the most probable location of the electron interaction within each pixel. Figure 3 shows the measured projected scatter angle for electrons traversing the Si detectors. The dashed histogram shows a simulation of 2 MeV electrons. Only the high energy electrons of ~ 2 MeV have sufficient energy to traverse 7 silicon boards and trigger the plastic scintillator shown in Figure 2. The resulting average projected scatter angle of $\sim 15°$ for 2 MeV electrons imply that the incident direction can be restricted to an arc of $\frac{1}{24}$th of the event circle. The energy loss and position in each silicon layer traversed is used to determine a direction-of-motion (DOM) parameter for each track (O'Neill et al. 1995). This parameter is used the same way that Time-of-Flight (TOF) is used for background discrimination. A DOM value can be determined for any recoil electron track in two or more layers. A measured DOM spectrum for ^{90}Sr electrons traversing more than 4 silicon layers is shown in Figure 4. In this case, the 92% of the events are correctly identified as downward moving.

A single coaxial Ge detector is used to provide an energy calibration for the entire multilayer array of Si detectors. In a double scatter (Compton telescope) configuration, the wide range of scatter angles provides an equally wide range of energy losses in the Si. Figure 2 shows the laboratory setup for calibrating seven 4 cm$\times$ 4 cm Si detectors while the insert in the figure shows the calibration results for a single strip of a single detector. The Si energy loss is found from the measured Ge energy of the scattered γ-ray and the source γ-ray energy. A ^{137}Cs energy spectrum obtained by this method is shown in Figure 5. The measured energy resolution is 10.8 keV (1σ) or 3.8%. This resolution will improve with the new 10 cm $\times$ 10 cm Si detectors and low noise triggerable (IDE AS) TA-1 chips with their trigger capability; for this particular experiment AMPLEX chips were used. The noise specification for the TA-1 should allow us to achieve 1.1 keV (1σ, 318 ENC) energy resolution. For 0.5 MeV electrons, where the total charge collected is 140,000 e in three layers, the energy resolution is 1.9 keV (1σ). This is to be compared with CGRO/COMPTEL's D1 resolution of 36 keV at 0.5 MeV, limited by the photoelectron statistics.

Simulation of Instrument Parameters: We have modeled the TIGRE instrument with the general-purpose MCNP code developed at LANL. The Klein-Nishina differential cross section in the code was modified to include the polarization dependence of the azimuthal angle of the scattered γ-ray. Energy resolutions for each individual Si and Ge detector element are taken as a conservative 3 keV (1σ) and 1 keV (1σ), respectively. The spatial resolutions are 0.75 mm and 2.0 mm, respectively. Thresholds of 30 keV for the Si and Ge detector element are used. For the CsI(Tl) shield and plastic scintillators 100 keV thresholds are used. The telescope γ-ray background was simulated and scaled to the level expected at an altitude of 40 km. The atmospheric flux obtained with a previous UCR balloon flight (Akyuz et al. 1997) was used. Event reconstruction is used to identify γ-ray with directions with in the instrument's FOV.

The absolute detection efficiency of TIGRE has a broad maximum of 5% and a high effective area of 80 cm^2 between 0.5 and 1 MeV. This is a factor of 2 larger than COMPTEL's value. All Compton events are either "tracked" or "non-tracked" depending on the number of silicon detector layers the recoil electron traverses. The percentage of tracked events increases from 50% at 0.5 MeV to >90% above 2 MeV. In the pair regime the efficiency remains constant with a value of 5%. At 60° zenith, the efficiency drops by 50%. The effective combination of shielding and kinematics reduces the background contribution from outside the FOV ($\sim \pi$ sr) by as much as two orders of magnitude. The Compton telescope's wide FOV allows it to be used as a survey instrument without orientation.

For Si/Ge events, at 511 keV and 1.8 MeV the energy resolutions are 4 keV (1σ) 8 keV (1σ), respectively. These values are slightly larger than the inherent single element resolutions when multilayer interactions are included. They are more than sufficient for most astrophysical spectroscopy applications. TIGRE's angular resolution as a conventional Compton telescope is represented by the distribution of event circle distances from the true source direction. At 500 keV, the angular resolution is 43 arc minutes (1σ), decreasing to 34 arc minutes at and above 1 MeV. Also important is the angular resolution along the event circle provided with recoil electron tracking. At 2 MeV, 92% of the 360° event ring can be eliminated as a potential source direction while at 10 MeV, 97% is eliminated.

TIGRE's electron recoil track direction allows us to augment the standard Compton event phase space with a fourth dimension to include information about the recoil electron. Ultimately, we need only the azimuth of the electron with respect to the scattered photon direction. A qualitative comparison of the TIGRE and COMPTEL point spread functions (PSF) is shown in Figure 6. We demonstrate TIGRE's point source sensitivity by using the maximum-likelihood ratio method to determine the minimum flux that can be imaged at the 3σ level for the exposure obtained during a 10^6s observation of a high Galactic latitude region of the sky. This is done for 0.3-100 MeV Compton and pair events, assuming an E^{-2} source spectrum and the expected background described above. These results are shown in Figure 7 and compared with other current and planned missions. TIGRE is well suited for a UNEX Ultra Long Duration Balloon Flight of ∼100 days.

References:

Akyuz A. et al. 1997, JGR, 102, No. A8, 17359.

O'Neill, T. J., et al. 1995, IEEE Trans. Nuc. Sci. 42, 933-939.

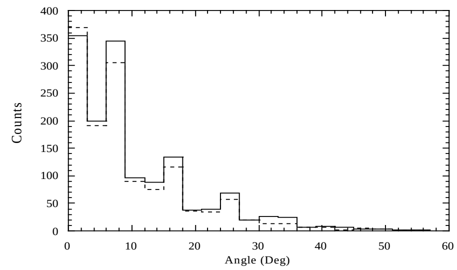

Figure 3: Measured and simulated (dashed line) electron projected scatter angles at 2 MeV.

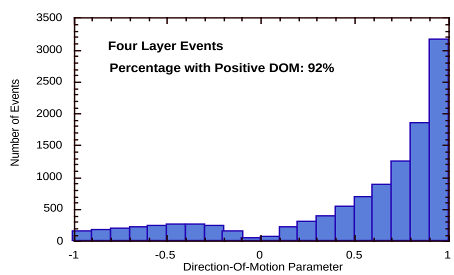

Figure 4: The distribution of the Direction-of-Motion (DOM) parameter for ^{90}Sr electrons. Positive DOM indicate the correct assignment of the direction of motion.

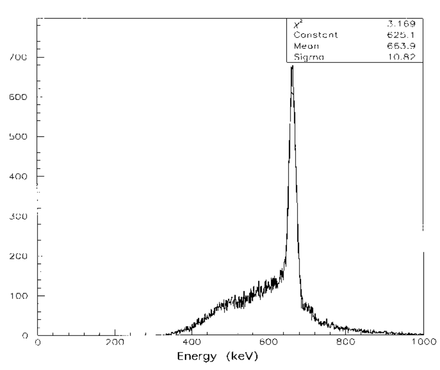

Figure 5: Spectrum of ^{137}Cs from the Si-Ge double scatter experiment.

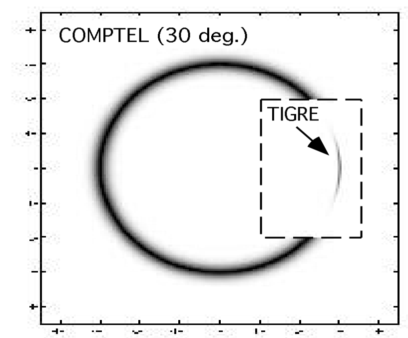

Figure 6: A comparison of TIGRE and COMPTEL PSF showing the great improvement in the incident photon directionality made possible by tracking the recoil electrons.

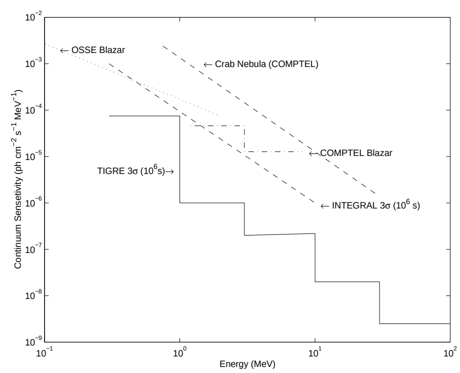

Figure 7: TIGRE continuum sensitivity for an ultra-long duration balloon mission.