Snowmass2021 - Letter of Interest

Double-Sided Silicon Strip Detectors for Next-Generation Gamma-ray Telescopes

Thematic Areas:

☐ (IF1) Quantum Sensors
■ (IF2) Photon Detectors
■ (IF3) Solid state tracking
☐ (IF4) TDAQ
☐ (IF5) MPGD
☐ (IF6) Calorimetry
☐ (IF7) Electronics ASICs
☐ (IF8) Noble elements
☐ (IF9) Cross Cutting

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Abstract:

This Letter of Intent describes the motivation for the continued development of double-sided silicon strip detectors (DSSDs). Silicon detectors have a long history of groundbreaking measurements in astroparticle physics, and in the new era of multimessanger astrophysics, they will continue to be instrumental through refinement in the MeV regime. DSSDs provide high resolution measurements of the position and energy of photon and charged particle interactions necessary to enable an MeV gamma-ray mission and bolster the advancement of mulitmessenger astrophysics.

Introduction

Fundamental questions about the smallest constituents in nature are only answerable through observations of the largest and most extreme objects in our universe. The Cosmos produces particles at an energy scale that is above and beyond what is achievable in laboratories here on Earth; the field of astroparticle physics is an integral branch of high-energy physics that allows for the study of the most extreme environments. From the conception of the field with Hess's discovery of cosmic rays, gamma-rays from $\sim$100 keV to $>$100 TeV have played a role in major discoveries.

The next frontier of astroparticle physics is multimessenger astrophysics: the combined study of astronomical objects with photons, cosmic rays, neutrinos, and gravitational waves (GW). In addition to advancements in neutrino and GW observatories, the science calls for complementary advancements in gamma-ray astrophysics, most notably in the MeV range. This is highlighted through the groundbreaking detection of the short gamma-ray burst and the neutron-star merger GW170817[1], as well as the temporally coincident detection of a cosmic neutrino and the flaring gamma-ray blazar TXS 0506+056[12]. These revolutionary results exemplify how observations in the MeV are key to further advances in astroparticle physics.

Gamma-ray telescope detector technologies

Much like the technology for terrestrial particle physics experiments, gamma-ray telescopes rely on the tracking of charged particles and high-energy photon interactions. From the first gamma-ray telescope which used a spark chamber, SAS-2[10] launched in 1972, to the modern day *Fermi*-Large Area Telescope (LAT)[4], which uses single-sided silicon semiconductor detectors, advancements in gamma-ray instrumentation follow the progress in particle tracker technology. *Fermi*-LAT, which is sensitive from $\sim$50 MeV to over 300 GeV, has made some of the most significant gamma-ray contributions to astroparticle physics to date[2;9]. Bringing LAT-like sensitivity down to the MeV regime (0.1-100 MeV) with new detector development is needed to boost multimessenger astrophysics[3;7;8;13;18–20].

To achieve sensitivity in the MeV gamma-ray regime, a telescope must be sensitive to Compton scattering interactions, in addition to pair conversion. This can be achieved with a *Fermi*-LAT-like geometry, utilizing a Tracker system to track charged particle products from gamma-ray interactions, and a calorimeter to measure the energy; see Fig. 1. However, Compton event reconstruction uses kinematic information from a sequence of scatters to determine the original direction of the photon[6], and thus the Tracker must give a precise measure of the energy ($\sim 5\%$ dE/E) and position ($\sim$ 1 mm) of each interaction. Since low-energy Compton-scattered electrons will not travel far before being fully absorbed, each segment of the Tracker (i.e. strips or pixels) must provide 3D position information for each interaction; therefore, single-sided silicon detectors do not provide sufficient information. The initial direction of the photon can be better constrained if the Compton-scattered electron subtends multiple Tracker segments allowing for a track to be measured.

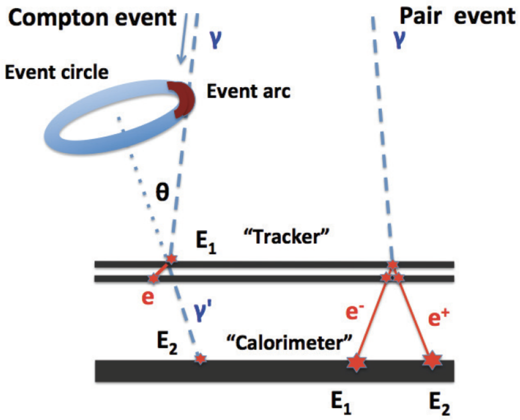

Figure 1: To advance astroparticle physics and explore the range from $\sim$100 keV to 100 MeV, a telescope must be sensitive to Compton scattering and pair conversion interactions. A standard design utilizes a tracker to measure the trajectory of charged particles coupled with a calorimeter to contain electromagnetic showers from high-energy events. Having many layers of double-sided silicon strip detectors (DSSDs) for the Tracker with high energy and spatial resolution allow for a precise measure of the Compton scattered electron and the track from electron/positron pairs.

Double-sided silicon detectors in astroparticle physics

There are four main advantages of using silicon detectors over other particle tracking detector technologies: 1) semiconductor detectors have excellent energy resolution, 2) silicon has good noise performance at room temperature, 3) silicon is a relatively inexpensive and ubiquitous detector material, and 4) low Z materials, such as silicon, have a high Compton scattering cross-section and small Doppler-broadening[21].

The accuracy of the Compton event reconstruction, and therefore the angular resolution and the sensitivity of an MeV telescope, depends on the precision of the energy and position measurements. The position resolution can be achieved through either double-sided silicon strip detectors (DSSDs) or pixelated silicon. While some particle physics experiments are investing in pixelated silicon detector technology, the data rate and power constraints that are unavoidable in a space environment are more easily met with DSSDs. Additionally, the Technology Readiness Level of pixelated silicon detectors is not advanced enough for the development of an MeV mission in the next decade. DSSDs constitutes the most promising and robust technology to advance astroparticle physics in the foreseeable future.

There is a history of DSSDs being used in space-based astroparticle physics instruments, for example, PAMELA[17] and AMS[22] have used DSSDs to study cosmic rays and dark matter. Most recently, the Hard X-ray Imager (HXI) on Hitomi flew six layers of DSSDs to achieve sensitivity from 5 to 80 keV[15]. In the early 2000's, there were a few efforts progressing towards an MeV telescope with DSSDs, most notably MEGA[5] and TIGRE[16]. However, neither of these proposed missions were sufficiently funded and development did not progress beyond the prototype stage. Two decades later, with advancements in detector technology and electronics readout, MeV telescopes based on DSSDs remain the most compelling design and the science is more pressing than ever.

The All-sky Medium Energy Gamma-ray Observatory (AMEGO) is a NASA Probe class mission concept that was submitted to the Astro2020 Decadal Survey and will provide ground-breaking new capabilities for multimessenger astrophysics.[14] AMEGO consists of four subsystems that work together to operate as a Compton and pair telescope: a DSSD tracker, a 3D position sensitive virtual Frisch-grid Imaging Cadmium Zinc Telluride (CZT) calorimeter, a segmented thallium-activated Cesium Iodide (CsI) calorimeter, and a plastic scintillator anti-coincidence detector. The AMEGO Tracker consists of 60 layers of 500 μm thick DSSDs with 500 μm strip pitch. Each layer contains four 4$\times$4 arrays of DSSDs, totaling 3840 silicon wafers each measuring 9.5 cm square. To mature this technology, the AMEGO team is building a prototype of the four subsystems and are working towards a balloon flight to test the instrument in 2021[11]; see Fig 2. There are a number of other international groups similarly advancing this technology.

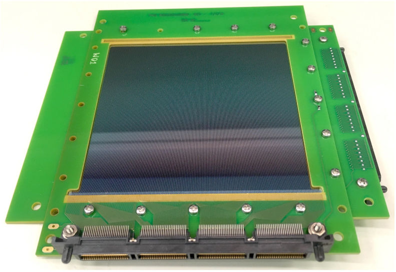

Figure 2: The AMEGO mission is a next-generation MeV telescope that is designed to enable multimessenger astrophysics. The AMEGO Tracker is designed around layers of DSSDs which measure the energy deposited from Compton scattering events and pair conversion interactions and is sensitive in the energy range $\sim$100 keV to $>$1 GeV. Prototype development of the Tracker is currently underway[11].

Conclusion

The next frontier of astroparticle physics is multimessenger astrophysics. With the planned advancements in neutrino and GW observatories, this science can only be enabled with a complementary advancement in gamma-ray telescope development. Building upon their illustrious history in astroparticle physics, DSSDs are poised to play the technological lead in the unfolding drama that is multimessenger astrophysics.

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