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A pair production telescope for medium-energy gamma-ray polarimetry

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ABSTRACT

We describe the science motivation and development of a pair production telescope for medium-energy ($\sim$5–200 MeV) gamma-ray polarimetry. Our instrument concept, the Advanced Energetic Pair Telescope (AdEPT), takes advantage of the Three-Dimensional Track Imager, a low-density gaseous time projection chamber, to achieve angular resolution within a factor of two of the pair production kinematics limit ($\sim$0.6° at 70 MeV), continuum sensitivity comparable with the Fermi-LAT front detector ($<3 \times 10^{-6}$ MeV cm^{-2} s^{-1} at 70 MeV), and minimum detectable polarization less than 10% for a 10 mCrab source in 10^6 s.

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1. Introduction

Since the launch of AGILE [1] and Fermi/LAT [2], the scientific progress in high-energy ($E_\gamma \gtrsim 200$ MeV) gamma-ray science has been extensive. Both of these telescopes cover a broad energy range from $\sim$20 MeV to >10 GeV. However, neither instrument is optimized for observations below $\sim$200 MeV or for polarization sensitivity. Ground-based air Cherenkov telescopes have been used to observe both galactic sources such as supernova remnants and extragalactic sources of very high energy (TeV) gamma-rays such as active galactic nuclei (AGN) [3]. They have provided important astrophysical information, but they also lack the capability to detect polarization. The Fermi and AGILE space-based telescopes, operating in the GeV energy range, are expected to continue to make significant progress for the next several years. However, there remains a significant gap in our knowledge of astronomy in the medium-energy ($\sim$0.1–200 MeV) regime between the X-ray and high-energy gamma-ray energy ranges.

The next major step in gamma-ray astrophysics, recognized as early as the SAS-2 era [4], should be a medium-energy gamma-ray pair production telescope to fill this gap and provide answers to many important astrophysical questions. In the following, we describe the science motivation for this mission and the design of the Advanced Energetic Pair Telescope (AdEPT) a pair production telescope for medium-energy, $\sim$5 to $\sim$200 MeV, gamma-ray polarimetry.

2. Science motivation

The AdEPT pair production telescope for the detection of medium energy ($\sim$5–200 MeV) gamma-rays with high angular resolution and polarimetry capabilities will open a new window in observational astronomy and astrophysics. Such an instrument can help provide answers to important questions in both astronomy and physics. For example, it can shed light on the origin and acceleration of cosmic rays, the nature of the cosmic-ray acceleration of electrons in the Crab nebula to energies in excess of 10^{15} eV [5] and how pulsars, with high magnetic fields and expected high gamma-ray polarization, achieve such high efficiency for particle acceleration. Gamma-ray polarization can distinguish between

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emission processes such as synchrotron radiation and other gamma-ray production mechanisms, however, the angular resolution with which the geometry of the gamma-ray emission regions are probed by polarization measurements is limited by the instrument angular resolution. It has long been expected that other astronomical sources such as "blazars" (a class of active galactic nuclei) should produce polarized gamma-radiation owing to the highly structured magnetic fields in their emission regions [6–9]. It is also known that gamma-ray bursts (GRBs) emit hard X-radiation whose polarization has been detected by space borne instruments, e.g. RHESSI [10], INTEGRAL [11], and GAP [12]. Such polarization should extend into the gamma-ray range, given the same basic emission processes. Observations at higher energies will investigate an underexplored energy range and provide new understanding of emission mechanisms with high polarization sensitivity.

Medium energy polarization measurements with AdEPT can also explore fundamental questions in theoretical physics. There is an apparent incompatibility between relativity and quantum mechanics at the Planck scale of 1.6×10^{-35} m. Effective field theory models developed to determine possible quantum gravity effects at observable energies, have led to the prediction of possible "vacuum birefringence", a process in which photons of different polarizations travel at slightly different velocities from an astronomical source. Such a process, if it exists at a significant enough scale, can destroy the inherent polarization of a source from which such polarization would be seen in its absence. Thus, the detection of polarization from a distant source such as a gamma-ray burst can constrain the possible existence of violations of relativity [13,14]. The birefringence effect is sensitive to the square of the photon energy. To date, the INTEGRAL/IBIS observations of the Crab pulsar and nebula at 200–800 keV [15] are the highest energy photon polarization measurements that have been made. An instrument capable of detecting polarization of medium energy gamma-rays can provide a much more sensitive probe of such relativity violations.

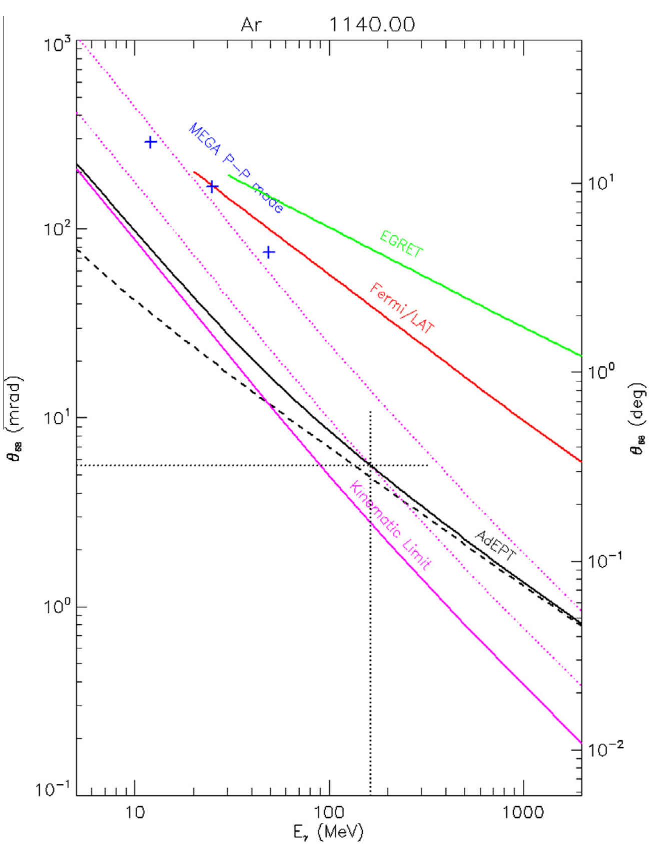

Fig. 1. The calculated angular resolution of the AdEPT telescope concept (solid black line, see Section 6 and Table 3) as a function of the gamma ray energy is the quadrature sum of the kinematic limit determined for nuclear pair production from [19] (solid magenta line) and the angular resolution limited only by MCS of the electron–positron pair (black dashed line). Twice, and five times the kinematic limit is also shown (dotted magenta lines). Below ~200 MeV, the AdEPT telescope will achieve angular resolution within a factor two of the kinematic limit. The MEGA [29] measured pair production angular resolution (blue crosses), EGRET [73] calibrated angular resolution (green line), and Fermi/LAT front [74] on-orbit angular resolution (red line) are shown for comparison. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The AdEPT pair production telescope also has significant advantages over previous attempts to measure the medium-energy diffuse extragalactic gamma-ray background. Possible contributing components [16] include non-thermal tails from Seyfert galaxies, red-shifted lines from Type Ia and Type II supernovae, and unknown extragalactic sources. Measurements by both the Apollo21 [17] and COMPTEL [18] instruments were plagued by intrinsic detector and spacecraft background problems owing to the buildup of long-lived radioisotopes created by cosmic-ray interactions. The subtraction of such poorly determined backgrounds led to uncertainties in the extragalactic background determination and significantly different results reported by the two different instruments. A free-flying argon gas AdEPT instrument is expected to have low intrinsic background similar to EGRET and Fermi/LAT and therefore yield a more reliable determination of the extragalactic gamma-ray background in the medium-energy range.

The 5-plus fold improvement in angular resolution of AdEPT below ~200 MeV compared with Fermi/LAT, see Fig. 1 will enable the numerous soft gamma-ray sources in the galactic plane to be better resolved improving the determination of the medium-energy Galactic diffuse emission and to spatially resolve variation between electron dominated and hadron dominated processes in the 70–200 MeV range.

3. Obtainable goals for exploring the medium energy gamma-ray universe

Significant improvement in sensitivity for pair telescopes can only be achieved through a dramatic improvement in the angular resolution, especially at lower energies. The ultimate angular resolution of any nuclear pair-production telescope is limited by the unobserved recoil momentum of the nucleus. The nuclear recoil momentum calculated by Jost et al. [19] for photon energy E_γ has a broad distribution extending from $2m_e^2/E_\gamma$ to E_γ, where m_e is the electron rest mass, and the nuclear momentum is nearly orthogonal to the gamma-ray momentum. On the assumption that the recoil momentum is transverse to the photon direction [20], an upper limit to the kinematic limit can be defined as q_{68}/E_γ, where q_{68} is the momentum above which 68% of the distribution lies. This simple assumption becomes less valid at energies below ~25 MeV where the momentum distribution is wider and the recoil angle is more acute. The kinematic limit and twice the limit are shown in Fig. 1 as the solid and dotted magenta lines, respectively. In the case of triplet production, i.e. pair production on the atomic electrons, the recoil momentum is, in most cases, observable [21] and the angular resolution is limited by the energy and spatial resolution of the electron track imager. Further discussion of triplet detection with AdEPT including effective area (enhanced for low-Z materials), angular resolution, and polarization asymmetry factor is beyond the scope of this paper and will be addressed in a future paper.