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All-sky Medium-Energy Gamma-ray Observatory (AMEGO)

Alexander Moiseev[1], for the AMEGO Collaboration
CRESST/NASA/GSFC and University of Maryland, College Park
UMCP, College Park, MD 20772, USA
E-mail: alexander.a.moiseev@nasa.gov
AMEGO website https://asd.gsfc.nasa.gov/amego/index.html

The gamma-ray energy range from a few hundred keV to a few hundred MeV has remained largely unexplored since the pioneering but limited observations by COMPTEL on the CGRO (1991-2000). Fundamental astrophysics questions can be addressed by a mission in the MeV range, from astrophysical jets and extreme physics of compact objects to a large population of unidentified objects. Such a mission will also provide critical inputs for multimessenger astrophysics by identifying and exploring the astrophysical objects that produce gravitational waves and neutrinos.

To address these questions, we are developing AMEGO: All-sky Medium Energy Gamma-ray Observatory, as a NASA probe-class mission, to investigate the energy range from 200 keV to >10 GeV with good energy (ranging from <1% at the low end to ~10% at the high end) and angular resolution (from 2 to 6 degrees depending on energy) and with sensitivity a factor of 20-50 better than previous instruments. Measurements at these energies are challenging, mainly due to the fact that two photon interaction processes, Compton scattering and pair production, compete. These interaction processes require different approaches in both detection and data analysis, and consequently in the instrument concept. AMEGO will be capable of measuring both Compton-scattering events at lower energies and pair-production events at higher energies. AMEGO will also have sensitivity to linear polarization of detected radiation at a level of 20% minimum detectable polarization from a source 1% of the Crab intensity, observed for 10^6 s. AMEGO will be operating mainly in scanning (discovery) mode with a field-of-view of 2.5 sr (20% of the sky observation any time), with the capability to be pointed to particular regions of interest.

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[1] Speaker. For the collaboration list see PoS(ICRC2019)1177

1. Introduction: Project Motivation

The Fermi Gamma-ray Space Telescope was launched on June 11, 2008, and since then its two instruments have been conducting all-sky γ-ray observations over eight decades in energy, from tens of keV to hundreds of GeV [1]. Fermi has transformed our understanding of the Universe in many aspects of high-energy astrophysics. The Fermi Large Area Telescope (LAT) has discovered more than 5,000 sources of various nature, recently presented in the 4th Fermi-LAT Catalog[2]. Fermi discoveries range from the most-distant and energetic objects such as Gamma-Ray Bursts and Active Galactic Nuclei, to starburst galaxies, globular clusters, a variety of pulsar systems, diffuse radiation in our Galaxy, solar flares and terrestrial γ-ray flashes. Many of Fermi's phenomena have not been unambiguously interpreted yet. For example, approximately one third of the Fermi-LAT sources remain unidentified, and the nature of the Fermi Bubbles is mysterious.

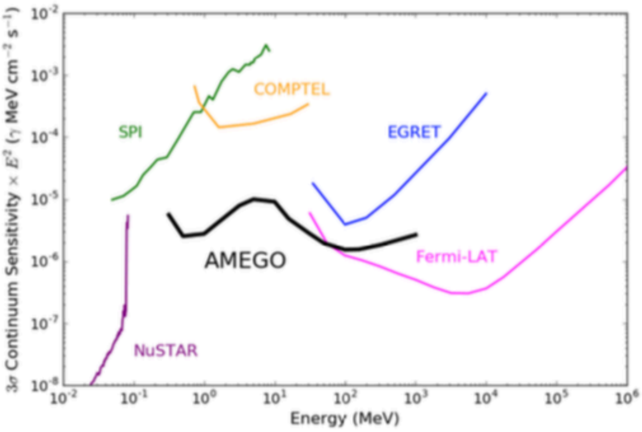

Figure 1. AMEGO 3 continuum sensitivity, calculated for 5-year mission and all-sky exposure. All other sensitivity curves are calculated for typical source exposure over the mission lifetimes

Fermi results have identified the directions for future investigations in γ-ray astronomy, namely the still underexplored MeV-range (**Fig.1**) with many potential discoveries hidden there: many astrophysical objects, such as blazars, pulsar systems and magnetars, have their peak energy output at lower energy than the Fermi-LAT energy range and thus constitute huge opportunities for discoveries (**Fig.2**).

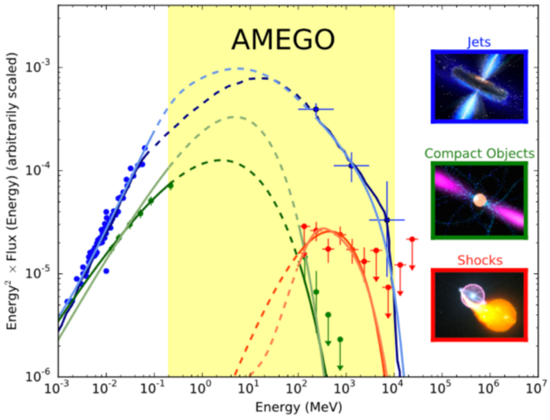

Figure 2. Characterizing the medium-energy gamma-ray band is essential to distinguish between spectral models and to understand the mechanisms that produce emission from jets, compact objects, and shocks.

Recent detection of a binary neutron star merger through the LIGO/Virgo detection of gravitational wave event GW 170817 and its short Gamma-Ray Burst counterpart and the likely identification of a non-stellar source of neutrinos (in collaboration with IceCube) ignited strong interest in MeV γ-ray observations, making them a critical contributor to multimessenger astrophysics by identifying and investigating the counterparts of such extreme phenomena.

The MeV domain remains one of the most

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[2] https://fermi.gsfc.nasa.gov/ssc/data/access/lat/8yr_catalog/

underexplored windows on the Universe not due to a paucity of interesting science but because the measurements at these energies are challenging. It is a range where two processes of photon interaction, Compton scattering and pair production, compete, with a crossover at around 10 MeV depending on the material. These two interaction processes require different approaches in both detection and data analysis, and consequently in the instrument concept. It is possible to design a cost-saving single instrument that will be able to use both kinds of photon interaction processes and provide accurate results in the extended energy range from ~200 keV to above 10 GeV.

2. Mission Definition and Key Science Objectives

AMEGO will fill in the critical gap at MeV energies in three overlapping capabilities (**Fig.3**)[2]:

- Continuum sensitivity from 200 keV to ~ 10 GeV, with a factor of >20 times deeper than COMPTEL in the overlapping energy range;
- Polarization sensitivity up to ~5 MeV, with Minimum Detectable Polarization of 20% for a source 1% the Crab flux, observed for 10^6 s;
- Energy resolution of 1-2% FWHM at 0.2-5 MeV, enabling nuclear spectroscopy, and 2-10% at higher energy

AMEGO will provide capabilities in all these areas more than an order of magnitude better than previous MeV γ-ray missions. AMEGO's observations, **combined with the new generation of gravitational wave and neutrino observatories, will lead to a revolution in multimessenger astrophysics.** Gamma-ray observations have already played a critical role in every multimessenger source identified to date – including γ-ray lines seen from SN1987A, a nearby neutrino source [3]; a γ-ray burst from the neutron star merger event GW170817A [4]; and a γ-ray flare from the active galaxy TXS 0506+056, the first identified counterpart to a high-energy neutrino source [5]. **It is difficult to predict what exact capabilities of the instrument will be the most important for such studies in about 10 years when AMEGO will start its operation, but with its high sensitivity and unique overall performance AMEGO be able to conduct the best possible and deepest exploration of critical MeV range, providing the major contribution to understanding the nature of any such phenomena.**

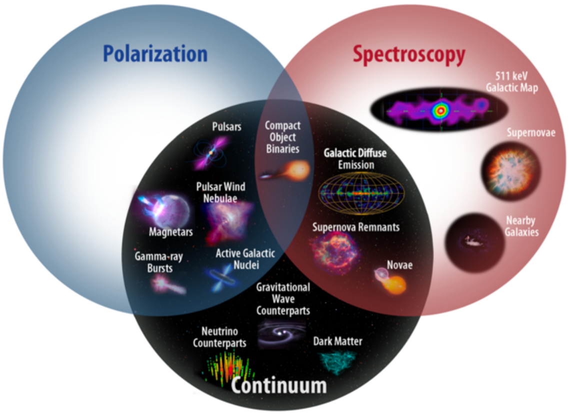

Figure 3. AMEGO provides three distinct capabilities in MeV astrophysics: sensitive continuum spectral studies, polarization, and nuclear line spectroscopy

The specific AMEGO scientific goals are:

a) **Understand the formation, evolution and acceleration mechanisms in astrophysical jets.** AMEGO will provide critical observations of the most massive black holes in the Universe, which are hosted at the centers of the most powerful objects known, active galactic nuclei

(AGN). The central black hole in AGN can have a mass up to a billion solar masses. *Blazars* are the AGNs where a jet points towards the Earth, making it bright in γ rays. A blazar has extremely high luminosity of $10^{42} – 10^{48}$ erg s^{-1}, originating in a relatively small volume. *All extragalactic sources of MeV* γ-rays *are candidate neutrino and ultra-high energy cosmic-ray sources: AMEGO with its MeV-sensitivity will detect over 500 long GRBs per year, and hundreds of blazars with peak power in the MeV band,* it will measure their spectra and variability with high sensitivity and link the observed characteristics to crucial physical parameters of these systems, such as the maximum energy to which particles are accelerated, the strength of the magnetic fields, the content of the jet, and the location of the γ-ray emission site. The polarization measurement capability of AMEGO provides a crucial test of the jet content, because hadronic models predict a much higher degree of polarization than leptonic models. *The detection and characterization of the MeV blazar population, combined with neutrino observations by IceCube and KM3NET, will be critical to understand nature's most extreme accelerators.*

b) **Identify the physical processes in the extreme conditions around compact objects.** *Neutron star (NS) mergers, which include both neutron star/neutron star and neutron star/black hole mergers, are the prototypical multimessenger events, producing gravitational waves* followed by both short γ-ray bursts and nuclear-powered kilonovae. Multimessenger observations of these cataclysmic events will probe sources of gravitational waves and astrophysical neutrinos, enable precision cosmology, and provide unique probes of fundamental physics, the origin of heavy elements, the behavior of relativistic jets, and the equation of state of supranuclear matter [6]. AMEGO will provide crucial electromagnetic capabilities to understand these sources (see [7] for a review). Another target area for potential breakthroughs is magnetar physics, provided by critical spectral and polarization features of the AMEGO.

c) **Element formation in extreme environments – kilonovae and supernovae.** Medium-energy γ rays provide a unique probe of astrophysical nuclear processes, directly measuring radioactive decay, nuclear de-excitation, and positron annihilation. The substantial information carried by γ-ray photons allows us to see deeper into these objects; the bulk of the power is often emitted at γ-ray energies; and radioactivity provides a natural physical clock that adds unique information. The process of Galactic chemical evolution is driven by the star-formation rate and the relative rates of dynamic nucleosynthesis sources, predominantly thermonuclear (Type Ia) and core-collapse (Type II, Type 1b/c) supernovae (SNe), along with kilonovae resulting from compact object mergers. AMEGO with its high line sensitivity can probe Galactic evolution, interstellar medium dynamics, propagation of cosmic rays, and relativistic-particle acceleration through γ-ray line spectroscopy measurements of short- and long-lived radioactive isotopes [8]. The nature of the progenitors of SN Ia and how they explode remains elusive. The lack of a physical understanding of the explosion introduces uncertainty in the extrapolations of the properties of SN Ia to the distant universe. Time-domain characterization of the emergent SN Ia γ-ray lines, well within the AMEGO observational capability, will help extract physical parameters such as explosion energy, total mass, spatial distribution of nickel masses, and ultimately lead to the astrophysical modeling and understanding of progenitors and explosion mechanisms [8].

AMEGO will be a powerful γ-ray observatory providing substantial new discovery capability to the scientific community. *AMEGO will continue the long-term monitoring of the* γ-ray *sky that* *the Fermi instruments have maintained for over a decade.* AMEGO's discovery potential derives from its combination of order-of-magnitude improvement in continuum sensitivity, advanced nuclear line spectroscopy, and γ-ray polarization capability [9, 10]; its superior angular resolution will help resolve the diffuse γ-ray emission that limits the sensitivity of Fermi-LAT analyses <300 MeV. Discovery is almost a foregone conclusion from this level of performance gain.

3. Instrument concept

To achieve the science described, we optimized an instrument design to enable sensitive continuum spectral and high-angular resolution measurements over a broad energy range from 200 keV to >10 GeV, with additional capabilities for measuring polarization and spectral lines (Table 1).

Energy Range	200 keV – >10 GeV
Angular Resolution	2.5° (1 MeV), 1.5° (5 MeV), 2° (100 MeV)
Energy Resolution (σ/E)	<1% (<2 MeV), ∼ 10% (1 GeV)
Field of View	2.5 sr (20% of the sky)
Line Sensitivity	1×10^{-6} ph cm^{-2} s^{-1} for the 1.8 MeV ^{26}Al line in 5 years
Polarization Sensitivity	<20% MDP for a source 1% the Crab flux, observed for 10^6 s
Sensitivity (MeV s^{-1} cm^{-2})	2×10^{-6} (1 MeV), 1×10^{-6} (100 MeV) in 5 years

Table 1. AMEGO performance

A distinct and unique feature of AMEGO is that it will detect γ-rays in both regimes, via Compton scattering at low energies <∼10 MeV and pair production at higher energies >∼10 MeV as sketched in **Fig.4.** In the Compton regime, AMEGO performance is provided by the 3D position-sensitive virtual Frisch-grid drift-bar CdZnTe Imaging calorimeter (CdZnTe Imager), and by the double-side Si-strip (DSSD) Tracker with analog readout. In the pair regime, AMEGO has been optimized for peak performance at lower energies around 100 MeV by removing foils between

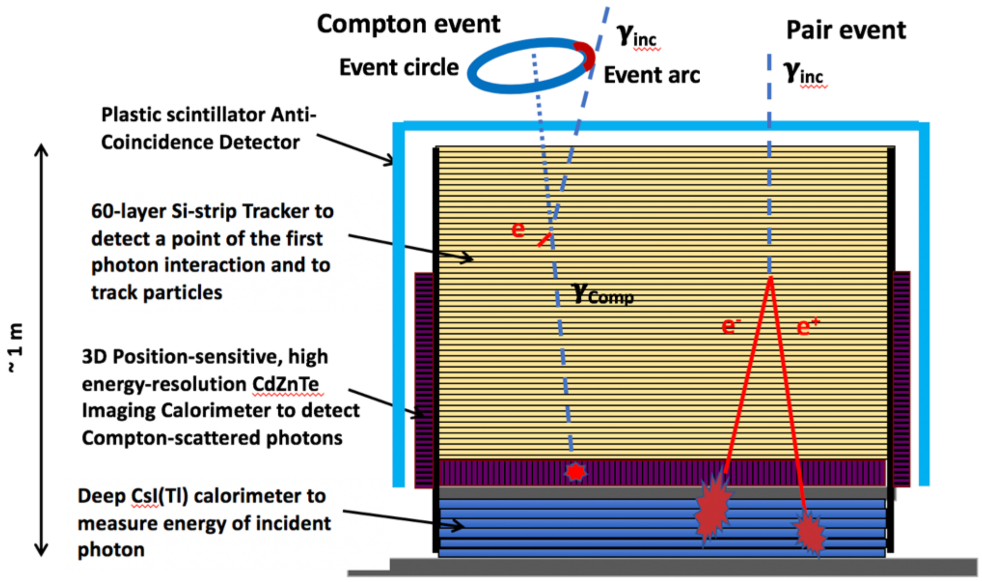

Figure 4. AMEGO concept, with schematically shown Compton and pair-production events

Tracker layers. Extension of the energy range to above 10 GeV is provided by the log CsI(Tl) calorimeter. Defense against charged cosmic-rays is provided by high-efficiency tiled plastic scintillator Anti-Coincidence Detector (ACD).

AMEGO principle of operation. An incoming photon either undergoes Compton scattering or creates an electron-positron pair in one of the Tracker Si layers (**Fig.4**). To improve low-energy performance relative to the LAT, analog-digital conversion is included in the electronic readout. Removing foils minimizes the amount of inert material in the detector, making it almost fully sensitive to the particle tracking, and also reduces multiple scattering of pair-production electron and positron, which is a major source of photon direction reconstruction uncertainty at energies below a few hundred MeV. The analog readout is needed to measure the energy loss by pair-production components and to measure the energy of the Compton-scattered electron, necessary to enable Compton measurements. Operation in Compton regime also requires the use of DSSD, to enable simultaneous measurement of both X- and Y coordinates of the first Compton interaction. As a result, the Tracker provides the coordinates of the first photon interaction and coordinates and energy of Compton electron deposited in the Si layer(s) for the Compton events, and coordinates and deposited energies for the pair components for pair-production events.

The CdZnTe imaging calorimeter lies directly below the tracker and surrounds the lower tracker layers. It carries the main load in enabling the Compton regime of operation by measuring the 3D coordinates of the scattered photon interaction and its energy (**Fig.4**). In combination with the information from the Tracker it allows reconstruction of the incident photon direction (circle or arc) and its energy. The side-wall layer boosts low-energy performance by enabling measurement of Compton events with large scattering angles where polarization is more pronounced. Polarization is determined from the azimuthal asymmetry of the scattered photon direction.
For the pair-production events the CdZnTe imager provides the measurement of the first 100-150 MeV of its energy, with the remaining energy (up to the GeV range) and electromagnetic shower profile measured by the log CsI(Tl) calorimeter, situated below the CdZnTe imager. In addition, the high-energy resolution CdZnTe imager enables measurement of nuclear lines, one of the strong capabilities of AMEGO.

The ACD detects incident charged particles with efficiency of >0.9997, providing the veto to the instrument trigger and thus suppressing 3-5 orders of magnitude cosmic ray flux compared to the γ-ray flux.

The AMEGO baseline main trigger is a coincidence of an over-threshold hit in the Tracker with the signal in the CdZnTe imager and absence of veto signal from the ACD. This trigger signals either Compton or pair-production photon event occurrence. The trigger has several modes with adjustable thresholds, to be set during the beginning of the mission, depending on the event rate and constrained by the downlink capability.

AMEGO consists of 4 identical towers. This design eliminates between-tower inert-material mechanical structure and electronics, both of which distort event images, especially in the low-energy Compton regime. Each tower contains the Tracker, the CdZnTe Imager, and the CsI(Tl) calorimeter, surrounded by the common ACD as a whole.

The Tracker consists of 60 layers, each containing a 4 x 4 array of DSSDs (per tower), each 9.5 cm square and 0.5mm thick with 0.5mm strip pitch. The DSSDs are wire-bonded on the top and the bottom with x- and y-strips and read out on x and y side. The layers are separated by 1 cm. This configuration was used to calculate the AMEGO sensitivity shown in **Fig.1**. Adjusting DSSD detector thickness, strip pitch and layer spacing results in trades between collection area, angular resolution, and field of view. A major task in the further development of AMEGO is to optimize these parameters to maximize both Compton and pair sensitivity.

The CdZnTe imager utilizes the virtual Frisch-grid bar approach [11 and references therein], while the face-to-face calorimeter thickness is achieved by using 8x8x40 mm bars to make up the calorimeter thickness [12]. The CdZnTe bars are operated in a drift mode that enables 3-dimensional reconstruction of the location of the interaction in the detector, thus providing good positional resolution (< 1 mm) as well as very good energy resolution (< 1% FWHM at 662 keV) at room temperature.

The imager is an array of modules, each containing 4x4 CdZnTe bars and served by individual ASICs. The modules are assembled side-by-side to make 40cm x 40cm tower array. As for the Tracker, the layout and geometry of the CdZnTe Imager will be optimized as part of the mission concept study. Additionally, a full study of the polarization capabilities will be performed.

The CsI(Tl) log calorimeter design is similar to the Fermi-LAT CsI calorimeter, but it significantly improves the low-energy performance by collecting the scintillation light with silicon photomultipliers (SiPMs). The CsI(Tl) calorimeter (each tower) consists of 6 layers of CsI(Tl) crystal bars 15mm x 15mm x 380mm arranged hodoscopically. The CsI(Tl) bars are wrapped in a reflective material to give high light collection efficiency, and the scintillation light is read out by a SiPM bonded at each end.

The ACD utilizes the same plastic scintillator as used on the LAT with wavelength shifting (WLS) strips and a SiPM readout. The current design assumes WLS strips inserted in grooves in each panel edge and viewed by two SiPMs, allowing uniform light collection. The alternative design is to use directly coupled SiPMs to the edges of the scintillator tiles.

The required degree of segmentation of the ACD, as well as the readout approach, will be addressed in detail later during the AMEGO design.

4. Summary

We are intensively working to propose the AMEGO for the Astro-2022 Probe Class Mission. The team consists of more than 200 scientists from 19 countries and 80 institutions, representing the world-wide γ-ray community. We recently submitted more than 10 white papers presenting in detail the science case for AMEGO, as well as the concluding Mission white paper. To support these actions, we are developing the instrument prototype to test the detection approach and the analysis and simulations packages. Special efforts are being made to develop the unique CdZnTe Imager. Both these activities are funded by APRA grants. We are preparing for the prototype beam test in late-winter of 2020, and the test balloon flight in the late-summer of 2021. The AMEGO simulations are based on the well-proven MEGAlib package, successfully used for several preceding similar projects such as MEGA, ACT, and COSI [13].

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