Megaelectronvolt astronomy with HERMES: spectroscopy, polarimetry, and synergies with fast Cherenkov arrays

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Abstract. Sensitive observations of energetic space phenomena in the 0.3 – 10 MeV range are needed to investigate a number of hot issues of modern astrophysics and cosmology. With the advanced technology of thick double sided silicon strip detectors (Si-DSSDs) it is possible to construct a space-borne gamma-ray telescope with sensitivity 30-100 times better than that of CGRO/COMPTEL. Synergies of MeV range observations from space with GeV-TeV range spectra to be obtained with future fast and sensitive imaging atmospheric Cherenkov arrays (CTA, TAIGA-IACT, ALEGRO) would allow one to reveal complex mechanisms of energy conversion in transient gamma-ray objects, in particular, sources of gamma-ray bursts. In this short note we briefly outline most demanding objectives of 0.3 – 10 MeV range astronomy and present a schematic view of HERMES gamma-ray spectrometer being developed at the Ioffe Institute.

1. Introduction

Gamma-ray astronomy is a prospective way to study fundamental physical processes accompanying fast energy conversion and release in a number of space objects. Despite its impressive potential for spectroscopic studies, allowing for sensitive diagnostics of the studied objects, an important part of the gamma-ray range – the sub-megaelectronvolt and megaelectronvolt (MeV) band – has been poorly explored as of yet, due to a number of fundamental and technological reasons. In two decades passed after CGRO/COMPTEL [1] no detector with a 0.3 – 10 MeV sensitivity exceeding that of COMPTEL was launched. The spectral resolution of now in orbit INTEGRAL/SPI camera [2] is high, but its 1 – 10 MeV sensitivity is quite low (see Figure 1).

Meanwhile, recent advances in detector technologies as well as development of compact, fast, low noise, and energy-efficient application-specific integrated circuits (ASICs), which are employed as front-end electronics for particle and photon detectors, has opened a new prospective for development of a new generation of sensitive space-borne gamma-ray telescopes. In particular, a number of projects of MeV domain instruments were put forward in Europe, USA, and Japan, such as GRIPS [3, 4], CAPSitt [5], PACT [6], ComPair/AMEGO [7], and e-ASTROGAM [8] based on Si strip detectors, DUAL [10] and ASCI [11] based on cooled Ge
Figure 1. Characteristic sensitivity of some existing and past detectors of hard X-ray and gamma-ray emission. The red line indicates the gamma-ray flux level $\approx 10^{-3}$ of the Crab Nebula.

detectors, and ETCT, where time projection microchambers were employed [12, 13]. However, none of such projects has been carried out by now.

A number of balloon flights with gamma-ray telescope prototypes have been performed since 2005 by the teams from Berkley and Toulouse. Those experiments were based on cooled Ge strip detectors [14–16]. However in 6–8 hours flights it was possible to detect 0.5 – 1.5 MeV emission from the Crab Nebula, it is not likely that a balloon-borne detector would achieve a sensitivity much better than that of COMPTEL even at the maximal realistic duration of such a flight (about 100 days).

Advanced technologies of radiation hard double-sided silicon strip detectors (Si-DSSD) have been developed at the Ioffe Institute [17–20]. Such detectors have been employed within accelerator experiments TOTEM and LHC at CERN; they are to be used within EXL and FAIR/SuperFRS experiments at GSI [21–23] and can be optimized for future space-borne measurements of accelerated particles and gamma-rays. Based on these developments, a team from the Ioffe Institute suggests to carry out a new space-borne gamma-ray telescope HERMES (High Performance MeV Spectrometer), which is expected to reach at least 20–30 times better sensitivity than COMPTEL in the 0.3 – 10 MeV range at angular resolution of about 1.5° and 3–5% spectral resolution. Sensitive observations in this range would allow one to study in detail gamma-ray lines from unstable isotopes and lines induced by interactions of cosmic rays with the interstellar medium. Hence, in 3–5 years of survey observations HERMES would address a number of hot issues of modern astrophysics, in particular, connected with evolution of matter and antimatter, i.e., physics of pulsars and black holes, generation of unstable nuclei in supernovae, transport of such nuclei and accelerated particles in the Galaxy, and the nature of dark matter. In contrast to the scintillation detectors of COMPTEL and solid Ge detectors of INTEGRAL/SPI, strip detectors to be used in HERMES would also allow one to measure
polarization degree of 0.5 – 5 MeV gamma-ray emission from energetic pulsar wind nebulae and transient, but bright gamma-ray burst (GRB) sources. Once combined by detections of GeV range emission by Cherenkov arrays, such measurements would yield deep insights of the nature of those objects.

In Section 2 main objectives of sensitive 0.3 – 10 MeV observations are briefly outlined, while in Section 3 we describe main functional blocks of HERMES, its target parameters and modelled characteristics.

2. Applications of Gamma-Ray Astronomy in the MeV Domain
Gamma-ray emission in the 0.3 – 10 MeV band carries important information on energy release and conversion processes in a number of energetic space objects, such as supernovae (SNe) and their remnants, pulsars and their wind nebulae (PWNe), active galactic nuclei (AGNs) and GRB sources. A unique feature of the considered band is the presence of a number of nuclear gamma-ray lines. Sensitive spectroscopy of such lines would allow one to determine various characteristics of the emitting medium: its composition, temperature, and density. Detection of redshifted gamma-ray lines from nuclei accreting into strong gravitational fields of compact degenerate stars would allow one to measure both their masses and radii and thus set constraints on the models of their internal structure (e.g., [24]).

The recent discovery of the accelerated expansion of the Universe, which was based on a detailed analysis of SNe Ia [25, 26] has put investigations of dark energy among most fundamental issues of modern physics. Tests of SN Ia nucleosynthesis models performed via observations of their gamma-ray emission in 0.75, 0.81, 0.85, and 1.24 MeV lines of $^{56}$Ni and $^{56}$Co are an important aspect of this issue. Apart from the dark energy issues, 0.3 – 10 MeV observations of all types of SNe are also of fundamental importance for the problem of the origin of chemical elements, for the star formation theory, and for the problem of cosmic ray origin.

Measurements of polarization degree of 0.3 – 5 MeV emission from GRB sources can be carried out with the Compton telescope technique. Such measurements would be a direct way to determine the dominating mechanism of this emission (see, e.g. [27]): detection of polarized MeV-range synchrotron emission from hadrons would indicate the presence of a hadron-dominated jet, while low-polarization inverse Compton emission from leptons would infer a Poynting-flux/magnetic dominated jet.

Sensitive 0.3 – 10 MeV observations with HERMES will be valuable for the following studies:
(i) Investigations of dark energy via the properties of the Hubble diagram at various redshifts by observations of calibrated sources of gamma-ray emission, such as GRBs and SNe Ia.
(ii) Search for dark matter particles with the gamma-ray profiles of neighbouring dwarf galaxies, of the Galactic Center and halo, as well as with distortions of gamma-ray spectra from distant objects due to photon-axion mixing in the intervening magnetic fields.
(iii) Investigations of intergalactic medium properties at high redshifts via observed gamma-ray emission from AGNs and GRBs: such studies would allow one to reveal physical conditions during the re-ionization epoch, and also at the stages, when proto-galaxies and first stars were formed, e.g., measure the star formation rate.
(iv) Investigations of baryon asymmetry in the Universe, in particular, generation and transport of positrons in the Galaxy via observations of gamma-ray emission in the 511 keV annihilation line, as well as positron distributions in central regions of active galaxies via observations of annihilation lines at higher energies.
(v) Investigations of cosmic ray origin in the Galaxy via observations of gamma-ray emission from exited nuclei; such observations would address important questions of the sources and composition of galactic cosmic rays, as well as of the mechanisms governing their injection into the acceleration processes.
(vi) Investigations of mechanisms governing extreme fluxes of electromagnetic energy in GRB
Figure 2. A schematic view of HERMES construction.

sources via measurements of spectral, temporal, and polarimetric characteristics of their emission at a reasonbably high spectral and temporal resolution.

3. HERMES: Target Parameters and Construction
To achieve the goals listed above, we envision development of a new generation MeV band gamma-ray telescope HERMES, whose target parameters are summarized in Table 1.

HERMES will consist of the following main subsystems schematically depicted in Figure 3: a) a 3D-tracker, where the incident gamma-rays will scatter off electrons inside Si-DSSDs; b) an outer anti-coincidence (AC) system, employed to veto tracker events arising from charged particles and induced radioactivity; c) onboard radiation hard front-end (FEE) and back-end (BEE) electronics, intended to read out the AC and tracker signals, do primary triggering and vetoing, preamplify the cleaned events, store and pass them to the telemetry subsystem of the spacecraft.
Table 1. Target parameters of HERMES telescope

| Parameter                                      | Value                                      |
|------------------------------------------------|--------------------------------------------|
| Sensitivity (in a 3 year survey)               | $<10^{-11}$ erg cm$^{-2}$ s$^{-1}$          |
| Spectral resolution                            | 3–5 %                                      |
| Angular resolution (0.5–8 MeV)                 | $1.5^\circ$–$2.0^\circ$                   |
| Field of view (HWHM, 0.5–8 MeV)                | $\sim 60^\circ$ ($\sim 3$ sr)             |
| Acceptance ($E = 1$ MeV)                       | $> 400$ cm$^2$×$3$ sr = $1200$ cm$^2$ sr  |
| Time resolution                                | $\sim 10$ µs                              |
| Minimal detectable polarization (1 MeV, 10 mCrab) | $\sim 15\%$                               |
| Proton rejection efficiency                    | $\sim 10^4$                                |
| Size, gross weight                             | $d < 150$ cm, $h < 100$ cm, $M < 350$ kg  |
| Telemetry rate (with compression)              | $\sim 64$ Gbytes/day                      |
| Maximal power consumption                      | $< 500$ W                                  |
| Orbit (optimal/acceptable)                     | L2/HEO                                     |
| Observation program (optimal/acceptable)       | whole sky/Galactic plane survey            |
| Estimated cost of main components              | $\sim 6 \times 10^7$ EUR                  |

![Figure 3](image1.jpg)

The tracker will consist of 100 sensitive layers, each of them made of 36 ($6 \times 6$) 1 mm thick Si-DSSD plates of $100 \times 100$ mm size (the size of the active region is $96 \times 96$ mm). The plates will be mounted into 4 quadrants divided by supporting surfaces of carbon-filled plastic and enforced with 5 mm thick Ti rods. In each layer of each quadrant 9 plates ($3 \times 3$) will be electrically bonded into ladders. The expected event location accuracy is about $2$ mm$^3$.

Modeling of HERMES has been performed with two specific tools: an original software based on GEANT4 [28] and the MEGAlib suite [29, 30]. The modelled effective area of HERMES and distribution of tracker event number are shown in Figure 3.
4. Conclusions

It is expected that during a 3–5 years term in orbit HERMES will allow us to construct a map of the 0.3 – 10.0 MeV sky and measure spectra of up to 1000 Galactic and extragalactic objects in this important but yet poorly studied domain. In particular, in such a term MeV range spectra of about 10 supernovae in the galaxies of the Local Group could be obtained, degree of polarization of MeV emission from a number of GRB sources could be measured. Such measurements would influence our understanding of stellar nucleosynthesis and of the amount of dark energy in the Universe. Other potential outcomes could include constraints on the amount of dark matter in certain extragalactic objects and birth rate estimates for protogalaxies and first stars during various cosmological epochs. Once carried out, simultaneous measurements of GRB emission with HERMES and future fast ground based Cherenkov arrays on the tens of seconds time scales would provide unique information on mechanisms of energy conversion and release, which govern particle acceleration and gamma-ray emission of these objects.

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