Improvement of sensitivity for MeV Gamma ray Telescope using Time Projection Chamber technology

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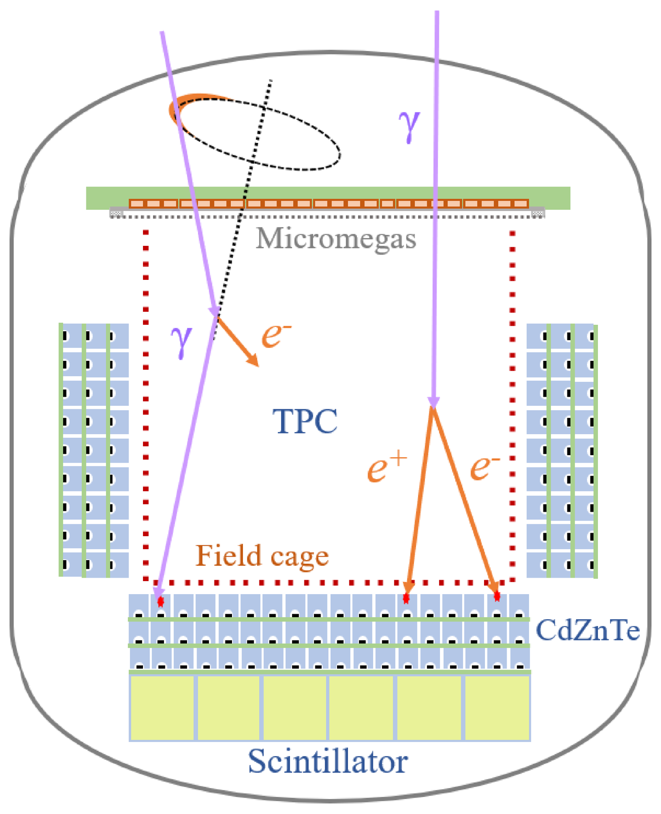
Abstract: The observation of gamma rays in the MeV energy band is crucial to astronomical research. There are fantastic scientific opportunities on dark matter detection, cosmic ray physics and gamma-ray astronomy via MeV gamma ray observations. MeV Gamma ray Telescope (MeGaT) is a new generation of high-resolution space MeV gamma ray detection telescopes by using Time Projection Chamber (TPC) technology surrounded by CdZnTe. Sensitivity is an important parameter of the telescope, which is related to angular resolution, effective area and the flux of backgrounds. The angular resolution includes the Angular Resolution Measure (ARM), Scatter Plane Deviation (SPD) and Point Spread Function (PSF). Thanks to the precise measurement of the direction of Compton recoil electron by TPC and Micromegas, the angular resolution of incident primary gamma and the sensitivity of MeGaT are improved.

Introduction

In astronomy, the MeV gamma ray band serves as a crucial observation window. Both supernovae and binary neutron star mergers emit gamma rays in this range, but results have large uncertainty due to complex interactions and low efficiency of discrimination between signal and backgrounds. Low-energy cosmic rays govern star formation and interstellar chemistry, but it is hard to observed beyond the solar system. Therefore, observing MeV gamma rays will greatly enhance our understanding of star origins and the universe's extreme environments.

MeGaT Detector System



MeGaT is a new generation of high-resolution space MeV gamma ray detection telescopes. The detector mainly consists of three parts:

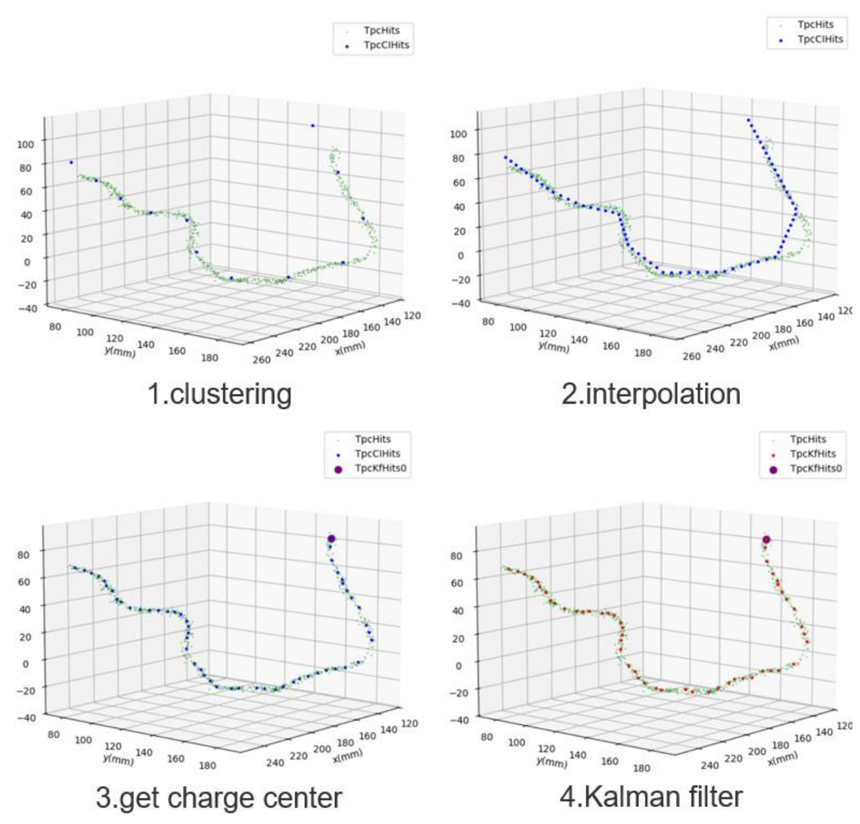
- TPC: track reconstruction for recoil electron
- CdZnTe: position reconstruction for scattering gamma and energy reconstruction
- Scintillator: energy measurement for high energy gamma which escape from CZT

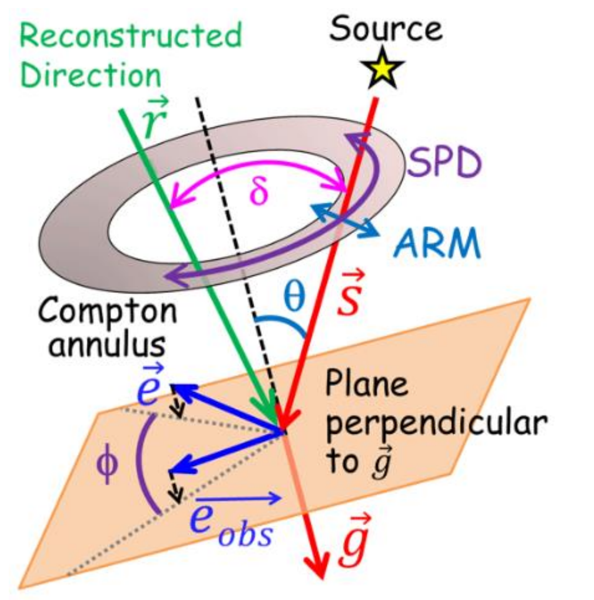
Simulation parameter	Value
Energy range of γ-rays	300 keV – 10 MeV
Size of TPC	50cm×50cm×50cm
Gas in TPC	97% Ar + 3% iC_4H_{10} (5atm)
Energy resolution of TPC	20% at 5.9keV (FWHM)
Size of CZT unit	1.72mm×1.72mm×10mm
Total thickness of CZT	3cm
Energy resolution of CZT	2% at 1MeV (FWHM)

Angular Resolution

Reconstruction process of the Compton scattering vertex and the initial direction of the recoil electron:

1. clustering: get the approximate direction of the track
2. interpolation: divide the track into smaller slices
3. get charge center: get the charge center of each slice
4. Kalman filter [1]: fine-tune vertex position and initial direction





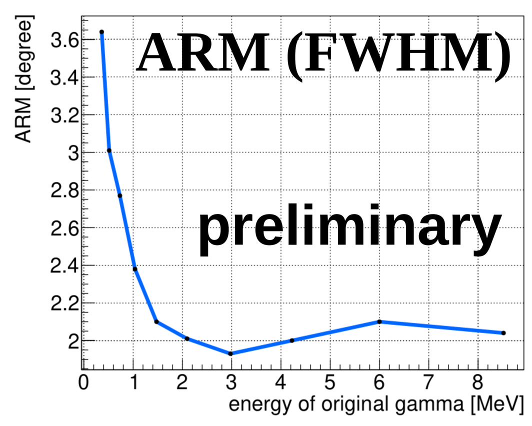
$$\Delta\theta_{ARM} = \cos^{-1}(\vec{S}\cdot\vec{g}) - \theta_{energy}$$

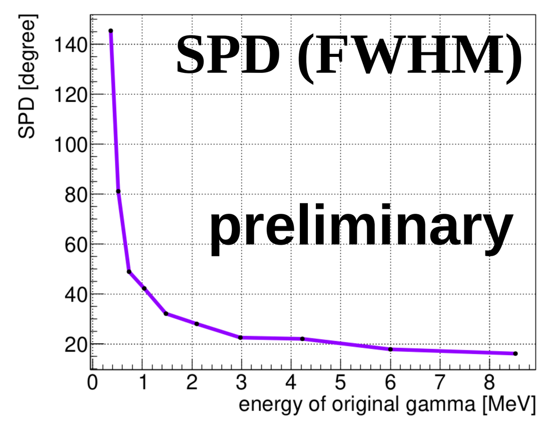
$$\Delta\phi_{SPD} = \cos^{-1}\left(\frac{\vec{g}\times\vec{S}}{|\vec{g}\times\vec{S}|}\cdot\frac{\vec{g}\times\vec{e_{obs}}}{|\vec{g}\times\vec{e_{obs}}|}\right)$$

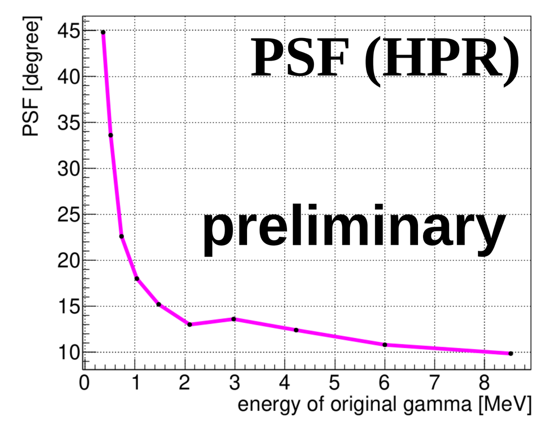
Definition of angular resolution [2, 3]

1. $\vec{S}$: the real direction of the original gamma
2. $\vec{r}$: the reconstructed direction of the original gamma
3. $\vec{g}$: the reconstructed direction of the scattering gamma
4. $\vec{e}$: the real direction of the Compton electron
5. $\vec{e_{obs}}$: the reconstructed direction of the Compton electron
6. θ_{energy}: the Compton scattering angle calculated based on the reconstructed energy of the scattering gamma and the electron

- **ARM:** the error of θ, corresponding to the width of the Compton annulus.
- **SPD:** the error of ϕ, corresponding to the radian of the Compton annulus (Compton arc).
- **PSF:** the error of δ.



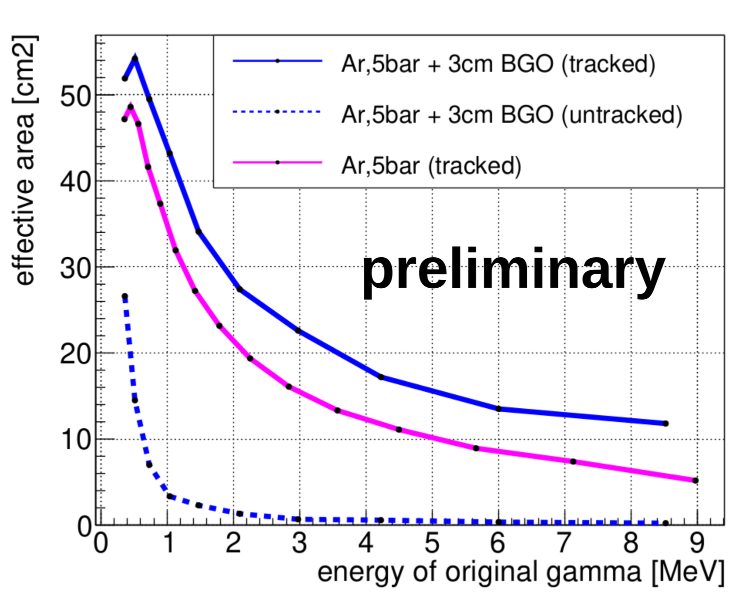




Effective Area

$$A_{eff} = \frac{n_{select}}{n_{total}} \times A_{simu}$$

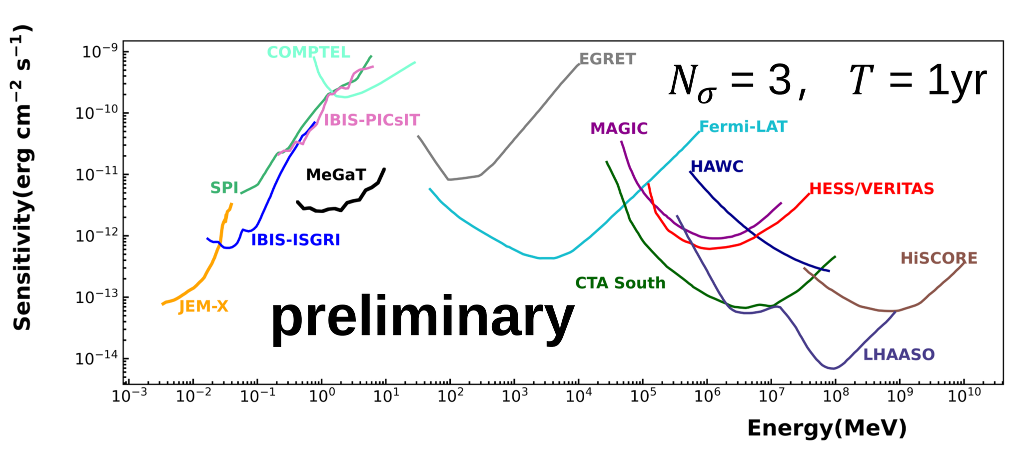
Selection criteria:
1. Compton interaction in TPC
2. full energy measurement in calorimeter
3. interact at TPC, CZT (or TPC, CZT, BGO) in sequence.
4. good trajectory of recoil electron by Kalman filter algorithm



Sensitivity

$$S = \frac{N_\sigma\,\sigma_\theta\,E^2}{\epsilon_{68}\,\Delta E}\sqrt{\frac{\pi\int B(E)dE}{A_{eff}\,T}}$$

σ_θ: angular resolution
A_{eff}: effective area
$B(E)$: the flux of backgrounds
N_σ: confidence level
T: effective observation time



Only Compton scattering is considered, and pair production is not included.

Conclusions

- Thanks to the precise measurement of the initial direction of Compton electrons by TPC and Micromegas, MeGaT has a good angular resolution.
- The PSF of MeGaT is 18° at the HPR for 1MeV. The ARM and SPD at the FWHM for 1MeV are 2.4° and 42°, respectively.
- The effective area at 1MeV is approximately 45cm². If Ar is replaced by CF_4 gas, the effective area will reach about 90 cm².
- The sensitivity of MeGaT is estimated to be more than an order of magnitude higher than that of existing experiments, and is about $3\times10^{-12} erg\cdot cm^{-2}\cdot s^{-1}$ at 1 MeV.

References

[1] Qibin Zheng, et al. Development of a 6D Kalman filter for charged particle tracking in time projection chamber without magnetic field. Radiation Detection Technology and Methods (2020) 4:70–77.
[2] Toru Tanimori, et al. Establishment of Imaging Spectroscopy of Nuclear Gamma-Rays based on Geometrical Optics. To appear in Scientific Reports 7, 41511; doi: 10.1038/srep41511 (2017).
[3] Andreas Christian Zoglauer, First Light for the Next Generation of Compton and Pair Telescopes.

Acknowledgement

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