Gamma-Ray Polarimetry in the Pair Production Regime

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Gamma-Ray Polarimetry

- Polarimetry is potentially valuable tool to supplement imaging, spectroscopy, and timing in high-energy astronomy
- Practically all high-energy astrophysical emission mechanisms should produce linearly polarized radiation: synchrotron, curvature, inverse Compton scattering, magnetic photon splitting
- All three gamma-ray detection mechanisms - photoelectric absorption, Compton scattering, and pair production - are sensitive to polarization through **azimuthal distribution of secondary particle momenta**
- Progress has been slow - limited by position resolution, number of readout channels, and multiple Coulomb scattering
- Breakthroughs finally occurring for photoelectric and Compton polarimetry
- Polarimetry should be possible for high-energy gamma-ray astronomy with pair production telescopes using gas micro-pattern detectors – time to think about value of polarimetry at a few 100 MeV

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High Energy (Pair) Polarimetry

- Pair production cross section depends on azimuth angle ψ of electron-positron pair plane with respect to polarization angle ψ_0:

$$\sigma(\psi) = \frac{\sigma_0}{2\pi}[1 + PR\cos(2(\psi - \psi_0))]$$

P = fractional polarization, $R \sim 0.1$ = inherent asymmetry

- For given azimuthal distribution, fit function of form $A\cos(2(\psi-\psi_0))+B$, define modulation factor

$$Q = \frac{N_{\max} - N_{\min}}{N_{\max} + N_{\min}} = \frac{A}{B}$$

(Then $P = Q_{measured}/Q_{100}$)

- Define *minimum detectable polarization* (MDP) as

$$MDP = \frac{n_\sigma}{Q_{100}S}\sqrt{\frac{2(S+B)}{T}}$$

n_σ = significance level, S = source rate, B = background rate, T = time

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Advantages of a Gas Detector

- Q_{100} exponentially suppressed by effects of Coulomb scattering:

$$\boxed{R' = R\, e^{-2\Phi^2}}$$

- Here $\Phi \sim 14L^{1/2}$ is the RMS change in ψ after traversing L radiation lengths (RL) of material. Due to thick converter foils, EGRET, AGILE, and GLAST have $R'/R \sim 10^{-4}$ or worse $\Rightarrow$ no polarization sensitivity
- $R'/R \sim 10^{-1}$ (for example) requires plane measurement within 6×10^{-3} RL
- Polarization sensitivity requires very low RL/sample ratio
- An **advanced pair telescope (APT)** can achieve arcmin imaging above 3 GeV if can achieve 2×10^{-5} RL/sample (Hunter, S. et al. 2001, AIP Conf Proc 587, 848)
- This requirement would imply ~300 samples in 6×10^{-3} RL $\Rightarrow$ should have useful polarization sensitivity
- **Such a low RL/sample ratio can in principle be achieved with gas detectors with very fine spatial resolution**

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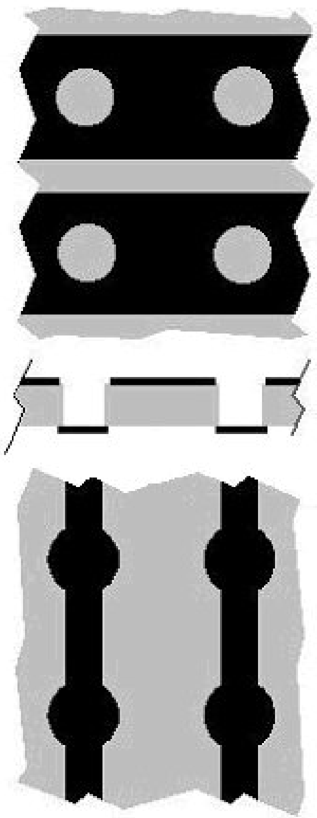
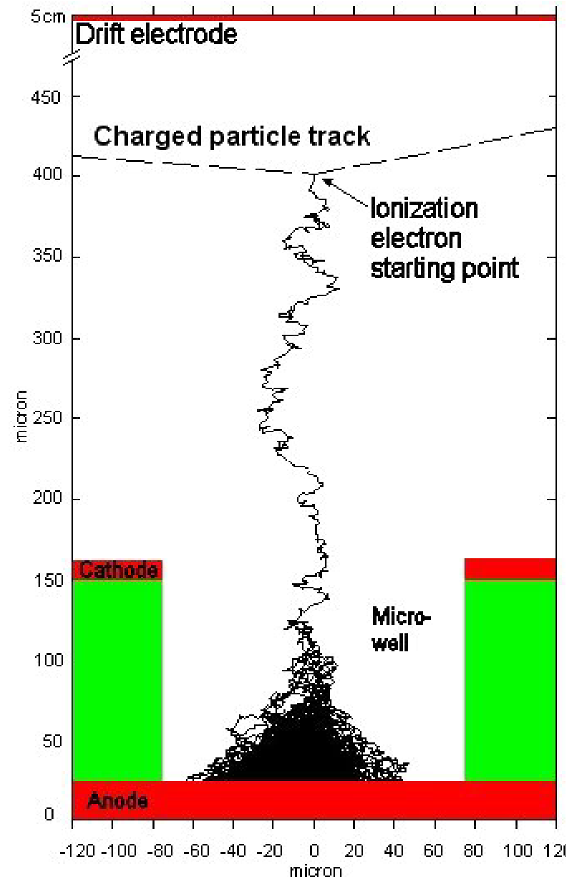
Gas Micro-Well Detectors



A type of gas proportional counter (related to the GEM detector)

- Cathodes and anodes are rigidly affixed to top and bottom of insulating substrate
- Open wells through cathode expose anode
- Pitch can be small (~200 μm) without electrostatic distortions
- Drift field and gain independently adjustable
- High gas gain (~10^4), stable operation
- Inherently two-dimensional
- Low-cost, low-power, rugged $\Rightarrow$ can read out large, fully instrumented gas volumes
- Drift electrode defines active volume
- Major development effort at GSFC over past 6+ years



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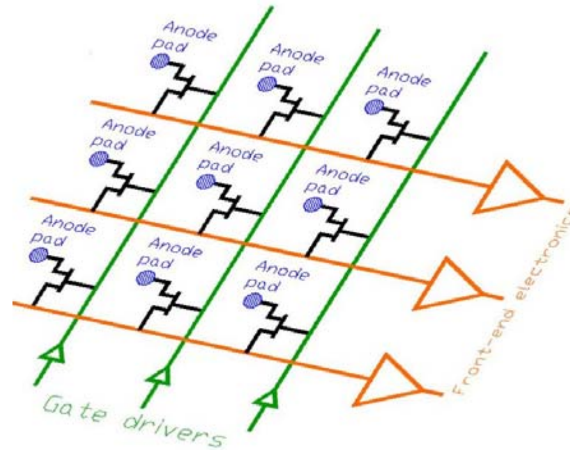
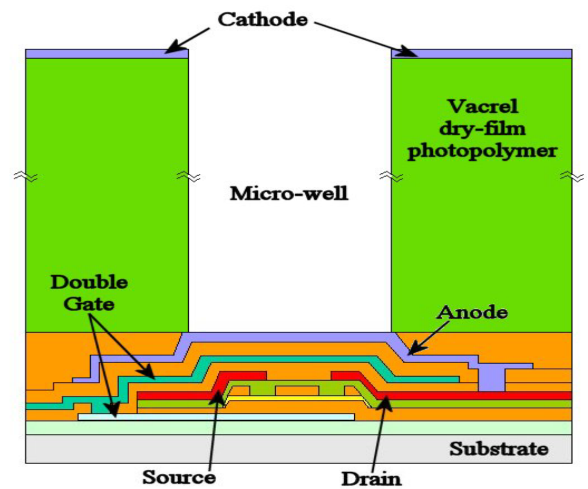
Pixelized Micro-Well/TFT Array

Crossed-strips not ideal for recording multiple charged particle tracks

Pixelized micro-well detector (PMWD):

- Anode segmented into pixels, corresponding to each well (cathode still strips)
- Each anode connected to an a-Si:H thin film transistor (TFT)
- Each column read out by selecting column (gate) driver; charge on anode pad collected by charge-integrating amplifier on each row
- Deposit anodes and cathodes directly on TFT array and create wells by etching
- Create arrays on polyamide $\Rightarrow$ rugged, low cost
- Good FET performance: $I_{on}/I_{off} \sim 10^8$
- Low power: FEE can be power strobed





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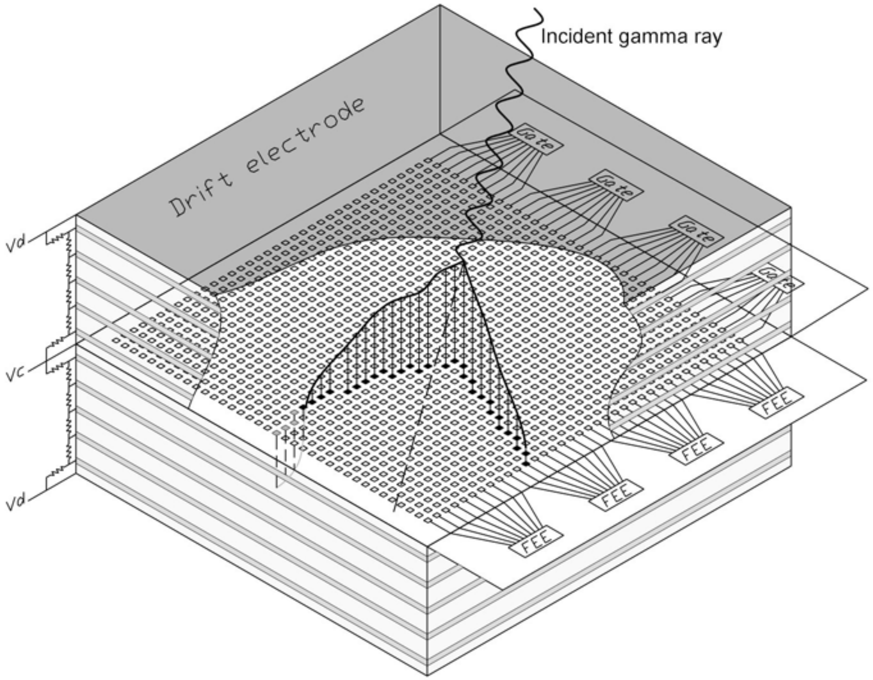
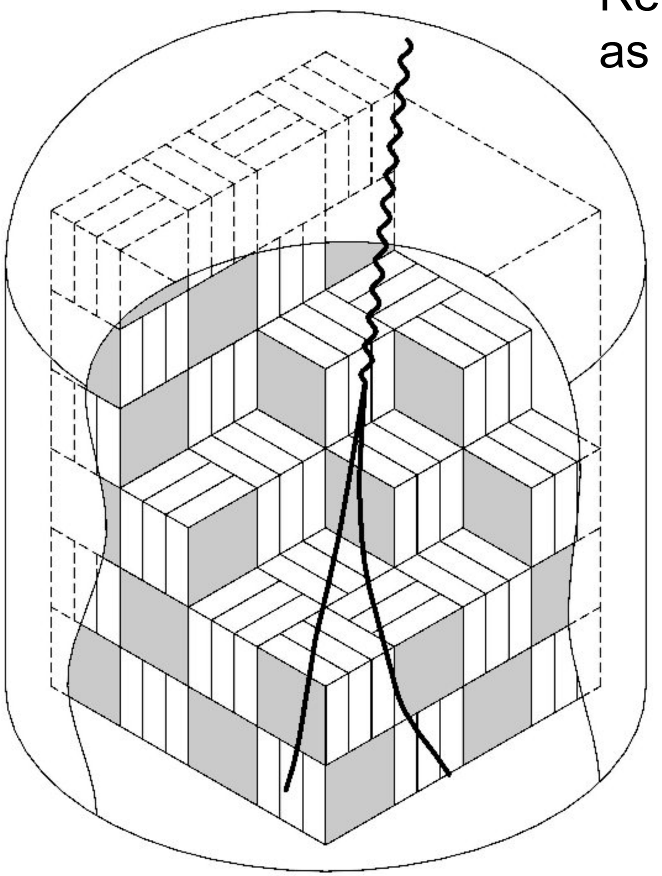
Three-Dimensional Track Imaging Detector (TTID)

- PMWD-TFTs provide a projected two-dimensional pair track image
- The third spatial dimension can be obtained by timing the drift of the ionization electrons
- Xenon scintillation from the pair tracks provides the start signal, and the prompt cathode signals provide the stop signals
- High density of channels and interconnects implies ASIC implementation for electronics
- FEE, gate drivers, and TPC electronics mounted on walls of module



3-D track imager (30 cm x 30 cm x 10 cm) as a module of a pair telescope tracker

Advanced Pair Telescope Concept



Requirement of 2×10^{-5} RL/sample achievable as follows:

- PMWD-TFT arrays with 200 μm well pitch
- Drift distance resolution ~ 140 μm
- Xe gas mixture at 1.5 atm pressure
- **6×10^{-3} RL = 6 cm = 300 pixels**
- TTID modules rotated 90^o relative to one another to provide “stereo” images of tracks
- 3 m diameter, 5.1 m depth to fit within reasonable launch fairing, provide 0.5 RL total interaction depth
- Pair energies derived from RMS of multiple scattering $\Rightarrow$ no calorimeter
- Use outer gas layer for anticoincidence $\Rightarrow$ no plastic shield

Geant4 Simulations of Polarized Pair Production

- Polarized pair production class written for Geant4 by G. Depaola and F. Longo
- Cross section for pair production, including polarization of incident photon and effects of non-coplanar events, derived analytically and computed numerically (Depaola, G. 2000, NIM-A, 452, 298) as function of azimuth angle ψ and non-coplanarity angle ϕ ($\phi = \pi$ for coplanar events)
- Derived surface parameterized by $\mathbf{f(\phi,\psi) = f_{\pi/2}(\phi)sin^2\psi + f_0(\phi)cos^2\psi}$, where $f_{\pi/2}(\phi)$ and $f_0(\phi)$ are functions of ϕ and energy, sampled in Monte Carlo method
- Used Geant4.5.1 with multiple scattering class from v3.2
- Simulations performed for gamma rays entering 5.1 m Xe volume. TTIDs represented by Kapton boxes (150 μm walls) with Cu electrodes (25 μm thick)
- Detector response applied to Geant4 output: electron diffusion, drift distance error, binning into 200 μm pixels, energy resolution
- Simple event reconstruction: 2 longest and straightest tracks found, fit with straight lines for as long as possible. These vectors are added, weighted by inverse of RMS scattering along tracks.

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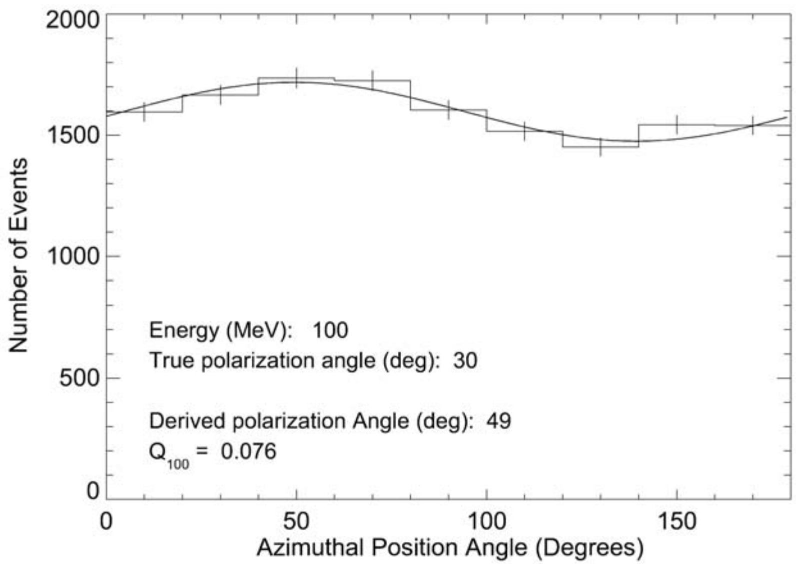
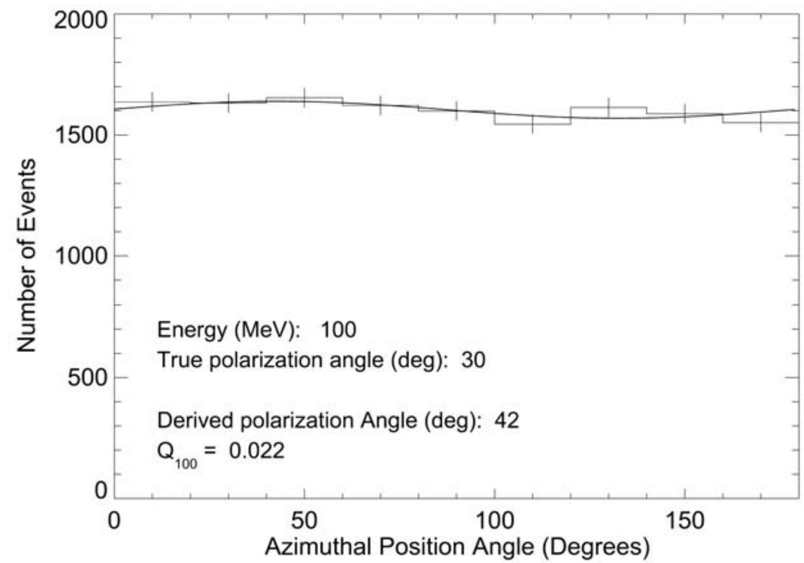
Simulated Azimuthal Distributions





- Raw azimuthal distribution from simulation - no scattering effects
- $Q_{100,raw}$ ~ 0.076
- Measured polarization angle is 49^o - shift due to non-coplanar events - can be calibrated

- Azimuthal distribution after tracks have traveled 6 cm = 6 x 10^{-3} RL
- Shows effects of multiple scattering
- Q_{100} ~ 0.022
- *R´/R* ~ 0.35 $\Rightarrow$ slightly better than estimate

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Best-Case Polarization Sensitivity

Estimate 3σ MDP at 100 MeV from best-case simulation results (no diffusion):

- Total pair detection efficiency is 21%, including event reconstruction
- Effective area is thus 11529 cm^2
- Angular resolution Θ_{68} ~ 2.0^o (also hurt by diffusion)
- Assume EGRET extragalactic background
- Assume Crab-like source, with $\Delta E = E$

Q_{100} = 0.076

MDP = 23% for 1 Crab in 10^6 s

MDP = 7.3% for 1 Crab in 10^7 s

MDP = 24% for 100 mCrab in 10^7 s

Q_{100} = 0.022

MDP = 80% for 1 Crab in 10^6 s

MDP = 25% for 1 Crab in 10^7 s

MDP = 84% for 100 mCrab in 10^7 s

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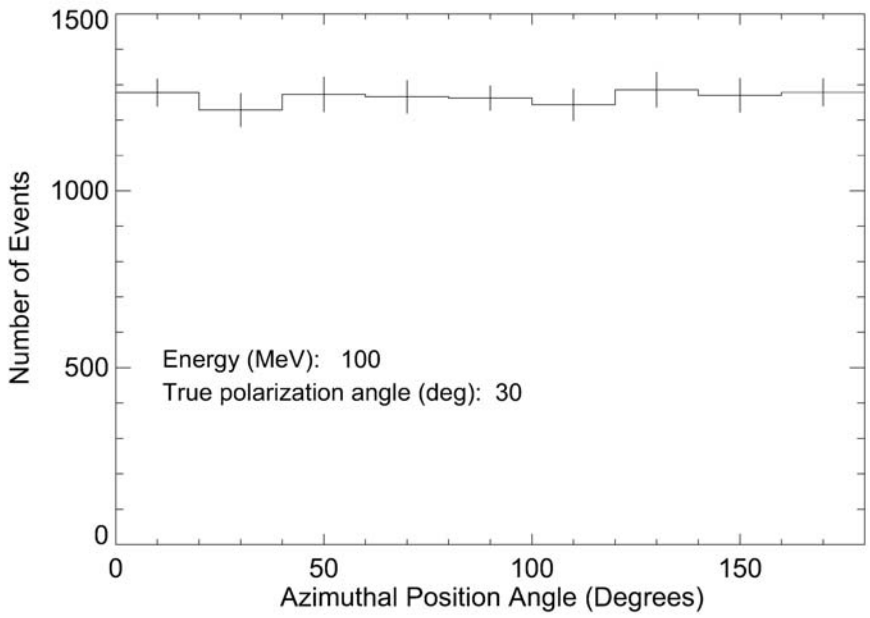
Problem: Diffusion of Drift Electrons

- Electrons diffuse as drift to wells – currently max drift distance is 5 cm
- Masks particle tracks, especially near vertex = most important part
- For transverse diffusion (Peisert & Sauli 1984):

$$\sigma_T \sim 0.6 \times (\text{Drift Dist (cm)/Pressure (atm)})^{1/2}\ \text{mm}$$

- After 5 cm drift, σ_T ~ 1.1 mm - tracks only separate by a few mm after 6 cm



RESULT:

- Azimuthal distribution after diffusion and event reconstruction
- Corrected by unpolarized simulation
- **No significant modulation**

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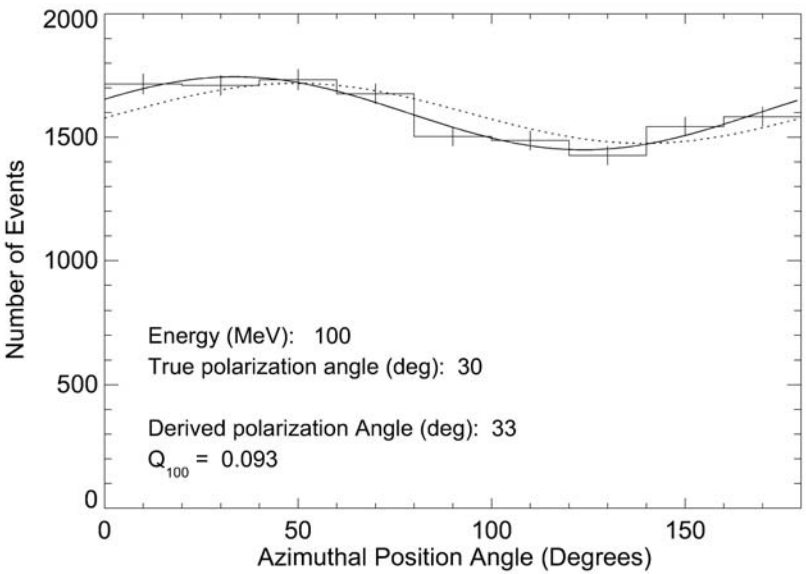
Possible Improvements

Increase Modulation?

- If could identify electron/positron (magnetic field?), can increase modulation
- Improvement not huge:



MDP = 19% for 1 Crab in 10^6 s

Reduce Diffusion?

- Reduce drift distance – but more channels, more passive material
- Increase pressure – but increases scattering, safety issues
- Negative ion drift (Martoff et al. 2000, NIM-A, 440, 355): addition of electronegative gas (e.g. CS_2) causes drift electrons to attach to ions, which then drift with much smaller diffusion – but drift *very* slowly (100 m s^{-1}) $\Rightarrow$ dead time problems

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Conclusions

- High-energy gamma-ray polarimetry is still very difficult
- Basic problems: low inherent modulation, low statistics, multiple scattering
- For gas detectors, main problem is diffusion of drift electrons
- Should be possible to track recoil electron from triplet pair production - only occurs ~ 1/Z ~ 2% of the time in Xe, but azimuthal distribution easier to determine - not yet implemented in Geant4
- Will continue to investigate ways to suppress diffusion and quantify required level
- Gas micro-well detectors also under investigation for the Advanced Compton Telescope (0.4 - 50 MeV) - good polarization sensitivity due to recoil electron tracking

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