Position Resolution in LaBr3 and LaCl3 Scintillators Using Position-Sensitive Photomultiplier Tubes

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Simulated Performance of 3-DTI Gamma-Ray Telescope Concepts

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***Abstract*— We present Monte Carlo simulations of two astronomical gamma-ray telescope concepts based on the Three-Dimensional Track Imager (3- DTI) detector. The 3-DTI consists of a time projection chamber with two-dimensional, crossed-strip micro-well detector readout. The full three- dimensional reconstruction of charged-particle tracks in the gas volume is obtained from transient digitizers, which record the time signature of the charge collected in the wells of each strip. Such detectors hold great promise for advanced Compton telescope (ACT) and advanced pair telescope (APT) concepts due to the very precise measurement of charged particle momenta that is possible (Compton recoil electrons and electron-positron pairs, respectively). We have investigated the performance of baseline ACT and APT designs based on the 3-DTI detector using simulation tools based on GEANT3 and GEANT4, respectively. We present the expected imaging, spectroscopy, polarimetry, and background performance of each design.**

I. Introduction

The next generation of medium-energy (0.5 – 50 MeV) and high-energy (30 MeV – 100 GeV) gamma-ray telescopes (Compton scatter and pair production telescopes, respectively) will require a substantial improvement in angular resolution in order to greatly improve on the sensitivity of previous and currently-planned missions. In both the medium- and high-energy cases, accurate imaging, which decreases the relative influence of background, relies on a good knowledge of the momenta of secondary particles produced in the primary gamma-ray interaction. These secondary particles are the scattered gamma-ray and recoil electron in the case of Compton scattering, and the electron-positron pairs in the case of pair production. Precisely recording these momenta also enables various background-rejection techniques and greatly increases the sensitivity of the telescope to the polarization of the incident radiation.

The angular resolution of the previous and current gamma-ray telescopes mentioned above is limited by multiple Coulomb scattering of the charged secondary particles within the detector materials which masks the particles' initial momenta. These factors have contributed to an enlarged point spread function (PSF) in current gamma-ray instruments and, in the case of pair production telescopes, have totally suppressed the polarization sensitivity. Improving this picture will require a low-density tracking medium with high spatial readout resolution. We therefore are investigating basing future gamma-ray instruments on micro-pattern gas detectors [1]–[5]. Here we outline possible designs for advanced Compton and pair telescopes using gas micro-well detectors currently under development at NASA/Goddard Space Flight Center (GSFC).

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II. Three-Dimensional Track Imager (3-DTI)

The gas micro-well detector (MWD) is a type of gas proportional counter based on micro-patterned electrodes. Each sensing element consists of a charge-amplifying well. The cathode and anode electrodes are deposited on opposite sides of an insulating substrate. The well is formed as a cylindrical hole through the cathode and substrate, exposing the anode. An array of such wells forms a detector. The active tracking volume is bounded by a drift electrode on one side and the wells on the other.

The Three-Dimensional Track Imager (3-DTI) is a concept for a time projection chamber (TPC) with a large area two-dimensional, crossed-strip MWD readout layer (Fig. 1). Charged particles traversing the TPC volume leave a track of ionization in the gas. This ionization charge drifts towards the MWD layer and into individual micro-wells where it produces an avalanche and thus the signals on the anode and cathode electrodes. The pattern of the wells which produce the signals is a two-dimensional projected image of the ionization. The third spatial dimension is obtained by timing the drift of the ionization charge.

The 3-DTI detector represents a departure from medium- and high-energy gamma-ray detectors currently under development. For example, the Medium Energy Gamma-ray Astronomy (MEGA) telescope [6] utilizes double sided silicon strip detectors to provide the Compton scattering medium and to track the recoil electron. A similar approach is used in the GLAST-LAT at high energies: tracking of the electron/positron pair is done with pairs of orthogonal, single-sided silicon strips [7]. Lead foils are interleaved with the silicon layers to provide the pair conversion medium. These approaches have a high density per measurement layer: 3.2 milli-radiation lengths (mRL) per layer for MEGA (0.3 mm Si per layer), and 26 mRL per layer for GLAST (LAT upper tracker, 2×0.3 mm Si + 1.12 mm

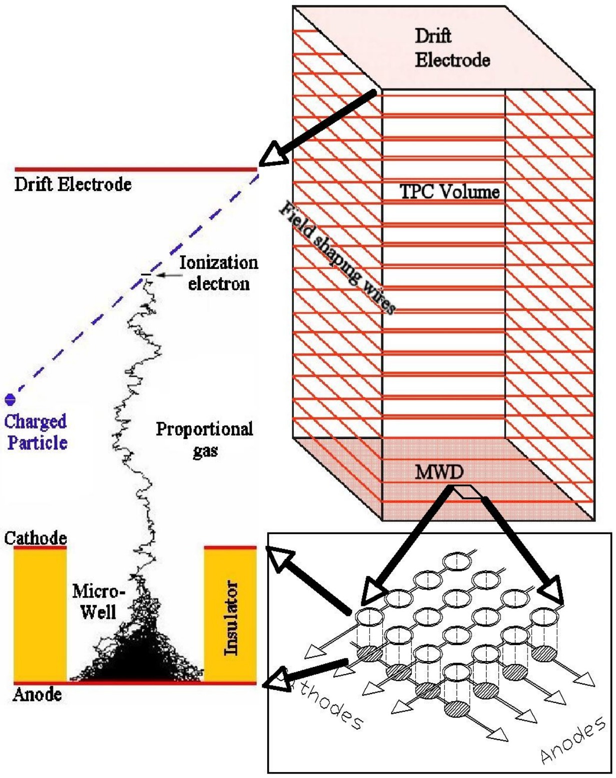

Fig. 1. The three-dimensional track imager. Energetic charged particle generate a track of charge which drifts into the wells of the MWD. Recording the time signature of the signals on the X and Y strips allows full 3-D reconstruction of the original track.

Pb). This contributes significant scattering to the electrons as they traverse the tracking layers. The active volume of 3-DTI detector, on the other hand, has no passive material and the interaction material is provided by the drift gas. For example, the 3-DTI, filled with xenon at 3 atm, has a density of 8×10^{-5} RL per 400 μm measurement resolution interval. Thus the 3-DTI provides several tens to hundreds of track measurements of the recoil or pair electrons before their direction is confused by scattering equivalent to even one MEGA or LAT track measurement layer.

The maximum allowable drift distance, and thus the active volume per readout channel, is limited by diffusion of the ionization charges as they drift to the MWD layer. Free electrons drift super-thermally; however, negative ion molecules remain in thermal equilibrium with the gas and, hence, have much lower diffusion. Carbon disulfide, CS_2, is a moderately electronegative molecule that has been shown to quickly scavenge the ionization charge, form negative ions that drift thermally, and, in the strong electric field of the micro-well, give up the electrons so that they produce a normal electron avalanche in the well [8], [9]. The admixture of CS_2 to argon reduces the drift velocity to $\sim$20 m s^{-1} at 4 V cm^{-1} torr^{-1}. The transverse diffusion coefficient is also greatly reduced. For 75% Ar + 25% CS_2, $\sigma_x \sim 0.008$ mm per $\sqrt{\mathrm{cm}}$ of drift [8], [9]. Similar reductions are expected for xenon + CS_2 mixtures. The dramatic decrease in σ_x due to this "negative ion drift" (NID) readily allows for an increase in the maximum drift distance to $>$100 cm for a single MWD layer.

The fabrication and lab testing of the 3-DTI and its readout electronics are reported elsewhere in these proceedings [10]–[12].

III. Monte Carlo Simulations of Advanced Gamma-Ray Telescopes

We have performed Monte Carlo simulations of two advanced gamma-ray telescope concepts to demonstrate the advantages of three-dimensional track imaging capabilities for improved background rejection, angular resolution, and polarization sensitivity. The two applications of gas tracking detectors are: 1) A tracker for an Advanced Compton Telescope (ACT) in which the recoil electron from the initial Compton scatter may be accurately tracked, greatly reducing the telescope's point spread function; and 2) an Advanced Pair Telescope (APT) whose angular resolution is limited primarily by the nuclear recoil and which achieves useful polarization sensitivity near 100 MeV.

A. Advanced Compton Telescope

1) Science Goals and Advantages of Electron Tracking: The Advanced Compton Telescope [13] is envisioned as a medium-energy gamma-ray mission with a $\sim$ 100-fold increase in sensitivity over that of COMPTEL, the only Compton telescope that had enough sensitivity to make astronomical observations [14]. The primary science goal of ACT is the study of gamma-ray lines from Type Ia supernovae (SNe Ia). In particular, the decay lines of ^{56}Co at 812 keV, 847 keV, and 1.238 MeV are important diagnostics of the SN Ia explosion mechanism. The lines are expected to be Doppler-broadened by 3–4% FWHM. A broad-line sensitivity of a few $\times 10^{-7}$ photons cm^{-2} s^{-1} in 10^6 s is the primary goal. Other science goals of medium-energy gamma-ray astronomy are described elsewhere in these proceedings [15].

Part of the required 100$\times$ increase in sensitivity can be achieved by accepting larger Compton scatter angles, increasing the effective area. The rest will have to come from a dramatic decrease in the telescope PSF, which reduces the area of the sky from which a given source's photons could have originated. This will reduce contamination from internal background, from diffuse cosmic and atmospheric gamma-rays, and from nearby astrophysical sources. There are two components to the PSF of a Compton telescope [2]. The first is the error in the computed scatter angle $\Delta\phi$. (This is often referred to as the angular resolution measure, or ARM.) The second component, $\Delta\theta$, is roughly given by the error in the measurement of the recoil electron's initial direction, projected onto the plane perpendicular to the scattered photon direction. The total angular area of the PSF is $A = \sin\phi\Delta\phi\Delta\theta$. The ACT must accept scatter angles up to $\sim 90^\circ$ or greater, and so good electron tracking may well be critical to keep the PSF, and therefore background, within reasonable limits.

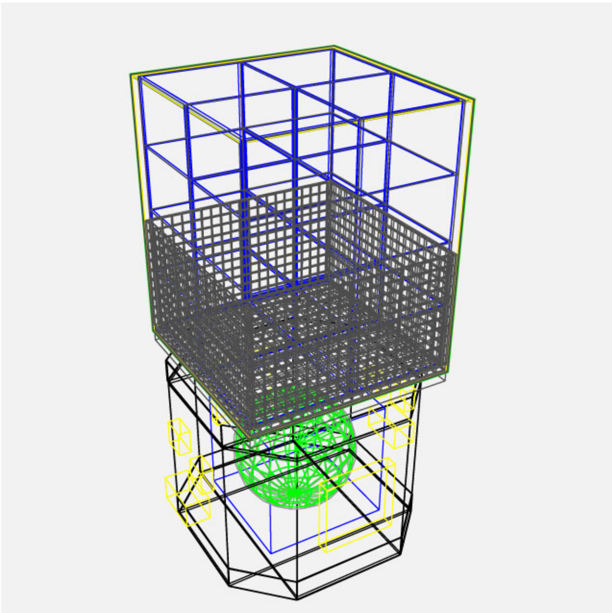

Fig. 2. ACT mass model used for MGGPOD simulations. It consists of a Xe gas tracker surrounded by a $LaBr_3$ scintillator calorimeter.

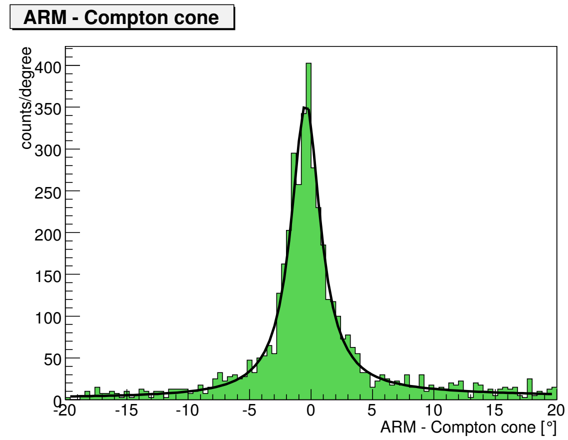

Fig. 3. ACT ARM distribution for events within a 836–870 keV window. FWHM = 2.8°.

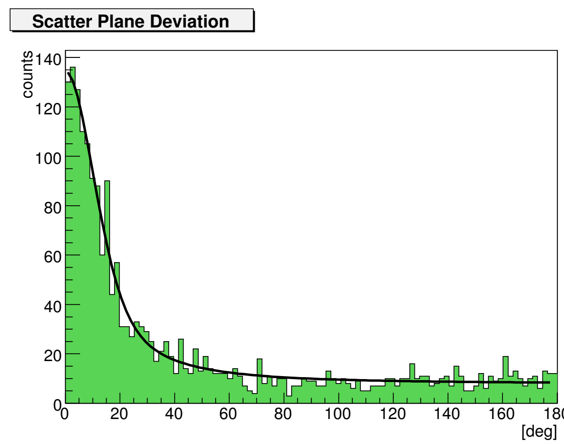

Fig. 4. ACT SPD distribution for all events within a 836–870 keV window. The 2.35σ width is 27.1°.

2) Monte Carlo Simulations and Estimated Performance: We have studied an electron-tracking ACT concept based on the 3-DTI detector using sophisticated Monte Carlo simulation tools. These tools have been developed as part of NASA's ACT Vision Mission Concept Study with the goal of evaluating and comparing different ACT detector technologies within a common framework [16]. The tools are based on the MGGPOD simulation package [17] and advanced Compton event reconstruction techniques [18]. This code is currently being converted to run on a Beowulf cluster at GSFC. The 847 keV line of ^{56}Co has been selected as a basis for evaluating performance.

Our ACT concept (Fig. 2) uses a gas 3-DTI tracker to record Compton scatter events and track the recoil electron, and a scintillator-based calorimeter to absorb the scattered photon. The tracker consists of 2 × 2 × 4 3-DTI modules, each 80 cm × 80 cm MWD area × 50 cm drift length. The tracker is full of 97% Xe + 3% CS_2 gas at 3 atm. The calorimeter is made of $LaBr_3$, a new scintillator material with high density, fast timing, and excellent energy resolution [19]. We assume 5 mm × 5 cmm crystals, 4 cm thick below the tracker and 2 cm thick on walls which extend 90 cm up the sides.

For our initial ACT evaluation we simulated incident photons with an energy of 847 keV. We require at least one hit in both the tracker and calorimeter. From the recorded energy spectrum of the 847 keV line we find an energy resolution of 3.4% FWHM. We evaluated the telescope tracking and imaging performance within an energy window of 836–870 keV. The angular resolution, defined as the angular resolution measure (ARM), the difference between the calculated and true Compton scatter angle, is shown in Fig. 3. The FWHM of the distribution is 2.8°. Another figure of merit for an electron-tracking telescope is the electron scatter plane deviation (SPD), the angle between the measured recoil electron direction and the true plane in which the photon scatters. This is shown for all events within the same total energy window in Fig. 4. The width of the distribution, defined here as a "FWHM" or 2.35σ, is 27.1°. We can also fit the SPD as a function of electron energy; for a power law fit, we find FWHM_{SPD}(deg) = 6.1 + 1845 × $(\mathrm{E(keV)})^{-0.9}$; this gives an spread of about 10° for a 1 MeV electron.

We next simulated the response of this ACT concept to a 847 keV line broadened by 3% for various zenith angles (with 0° defined as on-axis). We used an energy window of 829–887 keV. We found the effective area of the telescope for two cases: 1) using all events within the energy window and ±FWHM of the standard gamma-ray ARM distribution, and 2) using only those events within the energy window and ±FWHM of the "dual ARM" defined by both the gamma-ray ARM and the electron SPD. The results are shown in Fig. 5. The effective area falls off quite slowly with zenith angle, indicating that the telescope has a very wide field of view. The effective area is smaller for the dual ARM at all angles, but this is deceptive

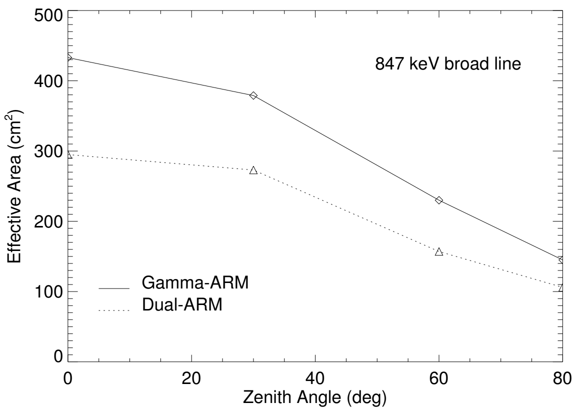

Fig. 5. Effective area of the ACT concept for a broad 847 keV line as a function of incident angle. The area is plotted for both the "standard" gamma-ray ARM and the "dual ARM," which includes the electron SPD.

since it ignores the background. We have begun background simulations using MGGPOD to determine the total sensitivity. So far we have simulated only the background due to gamma-ray photons from the diffuse cosmic background and from the Earth's atmosphere. Based on the number of photons from these sources that pass the same cuts used to derive the effective areas, we find that the on-axis 3σ sensitivity at 847 keV for a 10^6 s observation is 6.2×10^{-6} photons cm^{-2} s^{-1} for the standard gamma-ray ARM and 3.7×10^{-6} photons cm^{-2} s^{-1} for the dual ARM. Thus the ablility to track electrons provides a $\sim$67% improvement in sensitivity. We note that a gas-based ACT is the only concept able to track electrons at this low an energy. Whether or not a gas-based Compton telescope is capable of reaching a sensitivity of a few $\times 10^{-7}$ photons cm^{-2} s^{-1}, such an instrument is a strong candidate for an intermediate mission with a broader range of science goals [15].

B. Advanced Pair Telescope

1) Science Goals and High-Energy Polarimetry: Numerous science goals for high-energy (30 MeV – >50 GeV) gamma-ray astrophysics require greatly improved angular resolution over past or currently planned missions such as GLAST. The most basic of these goals is a complete census of high energy sources in the Galaxy, including a definitive distinction between classes of point sources and truly diffuse emission. A more ambitions goal is to map external galaxies (e.g. M31) in gamma-rays, allowing their source populations and cosmic ray distributions to be determined [20]. These goals will require an angular resolution roughly an order of magnitude better than that of GLAST, from $< 0.5°$ below 100 MeV to a few arcminutes near 1 GeV. Such resolution for single photons is possible using telescopes based on gas detectors. Above 30 MeV, gamma-ray telescopes form images by reconstructing the tracks of the electron and positron formed by pair production. The angular resolution of a pair production telescope is limited by the multiple scattering of the electron and positron in the detector material and by the unknown recoil of the particle (nucleus or electron) in whose field the pair conversion took place. It has been shown that a pair telescope can nearly achieve recoil-limited resolution, approaching 1 arcmin above a few GeV, if the density of the tracking medium can be made less than $\sim 2 \times 10^{-5}$ RL per track measurement interval [1]. In addition, a fraction of the pair conversions will take place in the field of an electron [21], and the track of this recoil electron will also be measurable in a low-density detector medium, allowing complete kinematic reconstruction of the event (so-called triplet production).

Polarization sensitivity will provide a new tool for high-energy gamma-ray astrophysics. Polarimetry provides information on source geometry, particularly anisotropies due to magnetic fields and particle distributions. Polarimetry is in principle possible with pair production telescopes due to the fact that the azimuthal orientation of the electron-positron plane is weakly correlated with the incident photon's electric field vector [22]. Past and currently-planned pair telescopes such as EGRET and GLAST, however, have negligible polarization sensitivity due to the multiple scattering of the pair particles in the thick converter foils, which quickly masks the original plane of the pair [23]. We have previously shown that a pair telescope based on gas detectors should in principle be sensitive to polarization from bright sources at $\sim$100 MeV [3].

2) GEANT4 Simulations and Estimated Performance: We have performed Monte Carlo simulations of an Advanced Pair Telescope concept based on the 3-DTI detector. Because pair production of polarized gamma rays is not implemented in GEANT3, we have used GEANT4 [24] for these simulations. Polarized pair production has been implemented in GEANT4 by G. Depaola and F. Longo [25], [26], and we have previously used their pair production class to evaluate a preliminary APT design [3].

The APT concept was simulated using 1 m^3 3-DTI modules divided down the middle by a drift electode, giving two 100 cm $\times$ 100 cm MWD area $\times$ 50 cm drift volumes. The modules were filled with 94% Ar + 6% CS_2 gas at 3 atm; Ar was used instead of Xe to maximize the cross section for triplet production, although this is not yet implemented in GEANT4. Eight modules were placed in a stack for a total length of 8 m, or ~ 0.25 RL. 100 MeV photons, 100% polarized, were simulated entering the APT stack on-axis with a polarization angle of 110°. The two longest and straighest tracks were found and fitted with straight lines near the vertex. The photon incident direction was found by the energy-weighted addition of these two fitted vectors, and the azimuth angle of the plane formed by the two vectors was calculated.

The results of the simulations are shown in Fig. 6 and Fig. 7. Fig. 6 shows the histogram of pair plane azimuth angles obtained directly from the raw simultion before applying the detector response and event reconstruction. This is, in effect, the "best possible case" result. A clear azimuthal modulation due to the polarized input is evident, and the modulation factor, defined as the (maximum - minimum)/(maximum +

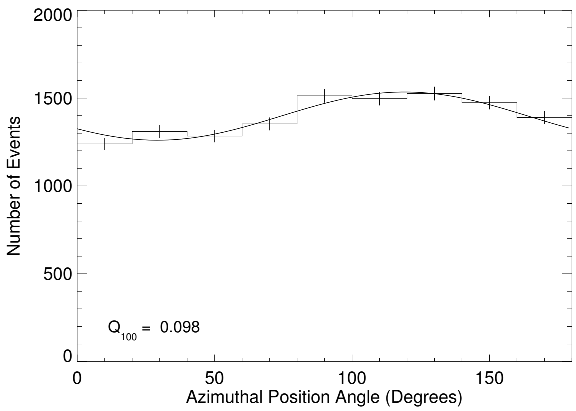

Fig. 6. True APT azimuthal distribution for 100% polarized, 100 MeV photons, taken directly from the GEANT4 simulation output before the detector response is applied. Measued polarization angle is shifted by $\sim 9°$ due to the effects of non-coplanar events. Modulation factor is 0.098.

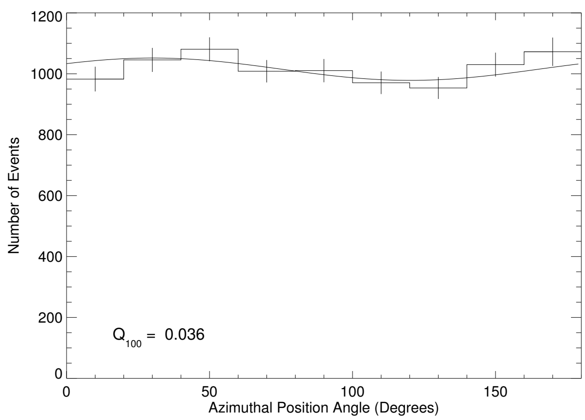

Fig. 7. Reconstructed APT azimuthal distribution, including the effects of the detector response and track fitting. The fitted modulation factor of 0.036 is not significant.

minimum) of a sinusoidal fit [3], is $Q_{100} = 0.098$. The measured polarization angle is $119.1°$; the shift from the input value is due to the effect of non-coplanar pair events and should be correctable [3]. The angular resolution, defined as the angular radius containing 68% of all events, is $\Theta_{68} = 0.6°$. Fig. 7 shows the same azimuthal histogram after the detector response and event reconstruction has been applied. Although the histogram still appears modulated, the angle is incorrect and the fitted modulation, $Q_{100} = 0.036$, is not significant. The angular resolution is $\Theta_{68} = 1.3°$. We believe this degradation in the telescope performance is due to problems with our simple track fitting procedure near the vertex, where the information about the initial particle momenta is preserved. We are currently developing a new track reconstruction fitting procedure based on maximum-likelihood fitting.

IV. Conclusion

We have demonstrated that three-dimensional track imaging detectors based on gas MWD hold great promise for future medium- and high-energy gamma-ray detectors. The development of MWDs into 3-DTI detectors is currently supported under a NASA APRA program at NASA/GSFC. This program supports the development of MWDs and their readout electronics as well as investigations of optimum gas mixtures, event reconstruction algorithms, and Monte Carlo simulations. A small prototype will be tested at a polarized gamma-ray beam this year. Further technology development will be needed to scale up MWD production and readout electronics to cover large areas, and to test larger prototypes at accelerator beams and on scientific balloon flights.

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