# A Compact Liquid Xenon Compton Telescope with High Energy Resolution and Time-Of-Flight

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## Abstract

Two recent developments have led us to propose a new type of Compton telescope in compact geometry with time-of-flight, for gamma-ray astronomy in the energy regime of 0.2 – 10 MeV. First, the technology of vacuum ultraviolet photo sensors for efficient and fast readout of liquid xenon (LXe) scintillation light has improved dramatically over the last few years, and new developments are underway. A LXe Advanced Compton Telescope would consist of two detector arrays of LXe time projection chambers in compact geometry, with time-of-flight (ToF) between detector modules at a resolution of order 100 ps. Second, the previously achieved moderate energy resolution in LXe, a significant draw-back for gamma-ray line spectroscopy, has been found to be largely due to a strong anti-correlation of ionization and scintillation in LXe. Efficient measurement of both charge and light enables us to improve energy resolution greatly. A factor of three improvement over a previous prototype, LXeGRIT, has already been achieved, and the measured underlying physics indicate the possibility of achieving energy resolution below 1% FWHM at 1 MeV. We are vigorously working on improving light and charge readout to realize this potential in a practical detector. Here, we report on the status and prospects of our current NASA research and development program.

## Motivation for Gamma-Ray Astronomy

Gamma-ray astronomy/astrophysics is still one of the least known about and less explored regions of the energy spectrum, yet many of the mysteries of the universe make themselves known at these energies. Nuclear γ-ray line transitions allow individual isotopes to be known, annihilation of electron-positron pairs can be studied, and the interiors of supernovae are able to be probed. Gamma-ray photons are highly penetrating, often traversing the length of entire galaxies before a single interaction. The problem with detection has always been small photon fluxes and large background noise. More efficient detection mechanisms at greater energy resolution and sensitivity are needed [7].

NASA is planning to launch the Advanced Compton Telescope circa 2015 to replace COMPTEL and CGRO. Its main goals are to study Sn Ia supernovae $^{56}$Ni abundances, probe the dynamics of supernovae explosions, and better estimate local Sn Ia rates as well as further study compact objects, GRBs, diffuse galactic nuclear lines, positron annihilation, and provide insight on locations of cosmic particle acceleration [7]. Studies continue to find the most reliable method of gamma-ray detection at greater sensitivities and lower energy resolution.

## An Overview of Radiation Detection in LXe

Owing to the fact that it is difficult to impossible to focus radiation at high energies (0.2-10 MeV) we must resort to either the photoelectric effect, Compton Scattering, or pair production in order to detect γ-rays. For the energy range of nuclear astrophysics, Compton Scattering dominates.

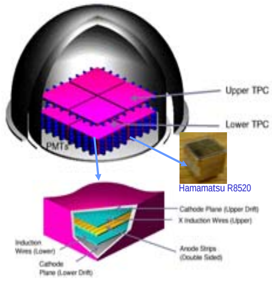
**Advantages of the LXeTPC Technology:**

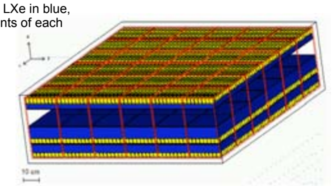
- Large uniform volumes with high active/passive ratio and 3D event imaging.
- Unique combination of fine 3D position, energy resolution and ToF for high S/N.
- "Easy" cryogenics at 165-180 K.
- Relatively low number of channels and low power per unit detector mass.
- Compact and Scalable: "clone" optimized unit module to make required area/volume.
- LXeGRIT = 1st version of a LXeTPC for γ-imaging. Valuable lessons from balloon flights [9]!
- Low internal background verified in flight.
- LXe is radiation hard and has high stopping power.

| Notable Properties | Lxe |
|---|---|
| Atomic Number Z | 54 |
| Density (g/cm$^3$) | 3.06 |
| Fano Factor (with Q-L anti-correlation) | 0.041 |
| Drift Velocity (mm/μs) @ 1kV/cm | 2.2 |
| W-value (ionization) (eV) | 15.6 |
| W-value (scintillation) (eV) | 14.7 |
| Wavelength of scintillation light (nm) | 175 |
| Dielectric Constant | 1.95 |
| Temperature Range (K) | 165-180 |

## Concept for LXeTPC for the Advanced Compton Telescope

Shown in the schematic to the right is an array of LXe Time Projection Chambers (TPC) in a compact geometry that would used on the ACT [7]. Each module is viewed by an array of square Hamamatsu PMTs for efficient light collection. The upper TPC will contain 3 cm of LXe while the lower 7 cm of LXe. There are a few techniques to reduce background, notably 3D event localization, Time-of-Flight (ToF), and Compton kinematics. As shown below, individual modules, vertically separated by a distance of 10 cm, would be 20-25 cm at the side and the array size could reach 2 x 2 m$^2$. PMTs are shown in yellow, LXe in blue, and structural elements of each tower in red.



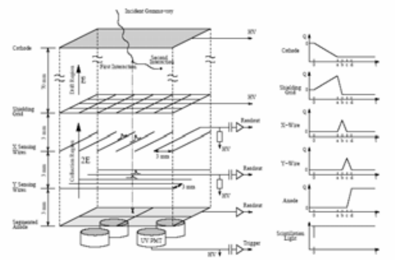


## New Developments in Photodetection

Avalanche Photodiodes (APD, left) have been used as an alternative to Photomultiplier Tubes since they have a higher QE and are not sensitive to vacuum or magnetic fields. APDs use semiconductor technology, as a weak pulse of light passes through the upper layer (p layer ~ 1μm) it creates electron-hole pairs as long as the pulse has sufficient energy to cross the band gap. The charges are accelerated in an electric field produced by stable HV which then collide with other atoms in the material freeing additional electrons. The process is repeated causing an "avalanche" of electrons to register a signal [2, 5].

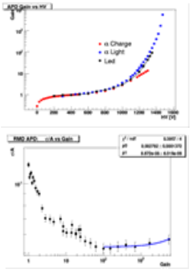
Silicon Photomultiplier Tubes (SiPM, center) use a 34x34 array of micro APDs (right image) representing individual pixels (1156) in a compact area (2mm x 2mm). Each pixel (micro-APD) has an area of 30x30 μm and operates in Geiger mode which helps to reduce noise levels and yields a high gain (~ $10^6$). [4] We are planning measurements to test their use in LXe. We expect excellent timing and high QE with low noise.

## Time Projection Chamber as a Compton Telescope



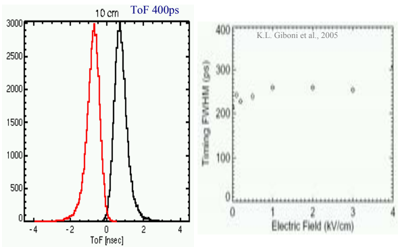
- An incoming γ-ray enters the detector and loses energy in multiple Compton scatterings and is then photo absorbed.
- 3D event localization and ToF allow sequence reconstruction.
- This enables operation as a Compton telescope, where Compton kinematics is used to reconstruct the direction of the incoming γ-ray.
- Scintillation light from the γ-ray 's loss of energy is detected by Ultraviolet Photomultiplier Tubes (UV PMT's) across the detector.
- In each interaction, a dense cloud of electrons is created through ionization. The charges are drifted in an electric field of 1 kV/cm until they pass through wire grids which determine the X-Y coordinates. The drift time with respect to the light signal provides the Z coordinate.
- The energy is measured on an anode where charges are collected or alternatively on the wires.

## APD as a Photo-sensor in LXe



Shown above is a large area APD from Radiation Monitoring Devices Inc. in the test chamber. Opposite the APD in the PTFE disk is an imbedded Po-210 α source and in between is a calibration LED. This APD was measured to have a QE of 34+/-5% for 175 nm light. The top-right plot shows signal gain versus bias voltage across the APD. Dark current was much reduced at the operating temperature of LXe and a maximum stable gain of 5600 was achieved. The bottom-right graph plots APD energy resolution as a function of gain from scintillation in LXe. The minimum energy resolution was 5.3% rms at a gain of 160 [5]. This is due to light collection variations for different positions of α interactions and non-uniform APD response. Measurements with an improved setup are underway.

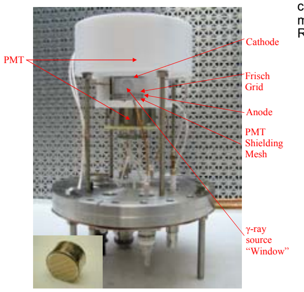
## LXeTPC Combined with Time-Of-Flight



The figure on the left is a simulation gathering scintillation light for one event registering in a histogram light collected from a forward and backward scattered event. The simulation was performed using compact geometry (~10cm spacing) which is needed for Compton Telescope implementation. The time between the forward and backward peak light is twice the ToF or 800 ps. Shown in the plot on the right is a timing measurement with two Hamamatsu R6041 PMTs in an LXeTPC versus electric field strength. Timing can be resolved to 100 ps. This enables sequencing of 2-interaction Compton events while improving the efficiency of multiple (3+) interaction events. ToF will also aid in background discrimination.

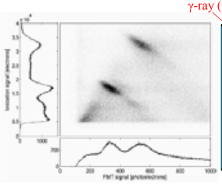
## Current Research

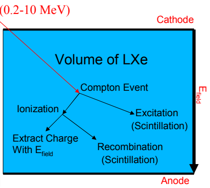
Shown at the right and below is Rice Universities one dimensional LXeTPC. It is designed to improve energy resolution by better quantifying the anti-correlation between scintillation light and charge collection in LXe. Two Hamamatsu R9288 UV PMTs (inset) are placed on either end of a sensitive cylindrical volume surrounded by PTFE. High voltage is placed on mesh grids between the PMTs. Source γ-rays are introduced through the side in a thin "window" between the cathode and Frisch grid. The entire apparatus will be submerged in LXe. This geometry will maximize light gathering through reflection while maintaining excellent charge collection.



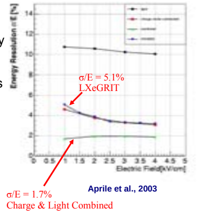
The charge signal will be amplified using a low-noise charge sensitive pre-amplifier which will be sampled by a Flash ADC system at ~ 10MHz. Light signals will be digitized using a fast (200 MHz) 12 bit FADC board on a VME system. A 365 nm UV LED will be pulsed to calibrate the PMTs. First measurements are expected within the next few weeks.

## Ionization versus Excitation in LXe





The figure on the upper right highlights the possible outcomes of a Compton interaction. If only charge is measured energy resolution is largely determined by the fluctuations between the number of ionization charges extracted and scintillation photons produced [6]. If both light and charge are measured, this anti-correlation can be overcome to fully exploit the spectroscopic potential of LXe, resulting in a Fano factor of ~0.04 [1]. This would result in energy resolution <1% FWHM at 1MeV.



Aprile et al., 2003

The effect of combining charge and light is shown in the figure on the upper left. In the regions where light and charge are combined yield a narrower FWHM than by charge or light collection alone [8]. An improved measurement is shown on the right. The challenge is to maximize light collection and at the same time minimize electronic noise. Both problems are being tackled in our R&D program (boxes below).

## Outlook

We are collaborating with the University of Milan to design an ultra-low noise pre-amplifier with the JFET front end inside LXe and will test it in the Rice TPC. Future projects include development of a 3D sensitive TPC module with enhanced light/charge collection and very good energy resolution. This may lead to a balloon-borne experiment carrying two of the LXeTPCs in compact geometry with ToF.

## References

[1] *T. Doke "Use of Sum Signals of Ionization and Scintillation in Liquid Rare Gases and the Fano Factor for the Sum Signals", NIM B234, 2005*

[2] *G.F. Knoll "Radiation Detection and Measurement", 3rd Edition, 2000 John Wiley & Sons, p. 29-55, 129-145.*

[3] *A. Curioni "Laboratory and Balloon Flight Performance of Liquid Xenon Gamma Ray Imaging Telescope (LXeGRIT)", Doctoral Thesis, Columbia University, 2003*

[4] *H. Miyata et al. "R&D of Calorimeters using Strip/Block Scintillators with SiPM", Calorimetry and Muons Session, LCWS05, 2005*

[5] *U. Oberlack et al. "Avalanche Photodiodes as Photosensors for Liquid Xenon Scintillation Light", In Preparation, 2006*

[6] *F. Xu "Development of a LXe-TPC Compton Telescope for Gamma-Ray Astronomy", Doctoral Thesis, Columbia University, 1998*

[7] *S. Boggs et al.(ACT Collaboration) "Advanced Compton Telescope: Witness to the Fires of Creation", NASA Mission Concepts Study, 2005*

[8] *E. Conti et al. "Correlated fluctuations between luminescence and Ionization in liquid xenon", Phys.Rev.B 68, 054201, 2003*

[9] *E. Aprile et al. "Calibration and in Flight Performance of the Compton Telescope Prototype LXeGRIT", New Astron. Rev. 48, 257, 2004*

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