PETALO: TIME-OF-FLIGHT PET WITH LIQUID XENON

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WHY LIQUID XENON?

RESPONSE TO IONIZING RADIATION

- Excellent scintillator.
- Two responses to ionizing radiation: scintillation and ionization (anticorrelated).
- Transparent to its own scintillation light.

- VUV scintillating photons emitted from one of the two lowest electronic excited states (singlet and triplet) to the ground state.

\[
\begin{align*}
\text{LXe} &
\text{R} &
\text{Ex} &
\begin{array}{ll}
1\Sigma_u^+ & 3\Sigma_u^+ \\
34 \text{ ns} & 2.2 \text{ ns} \\
& \text{with } E \neq 0
\end{array} \\
29 & 1.4 & 27.6 & 27 \text{ ns} \\
& \text{with } E = 0
\end{align*}
\]

\[
e^- + \text{Xe} \rightarrow \text{Xe}^* + e^- \\
\text{Xe}^* + \text{Xe} \rightarrow \text{Xe}_2^* \\
\text{Xe}_2^* \rightarrow \text{Xe} + \text{Xe} + h\nu
\]
WHY LIQUID XENON?

RESPONSE TO IONIZING RADIATION

It can be modelled as 2 exponentials: \( \tau_1 = 2 \text{ ns} \), \( \tau_2 = 43.5 \text{ ns} \) (3% and 97%).
THE PETALO PROPOSAL

a Positron Emission Tomography Apparatus based on Liquid xenOn

- Using liquid xenon as scintillation medium.
- Scintillation light only.
- Silicon photomultipliers.
- Spin-off of the @next experiment.

- Fine granularity for spatial resolution.
- Fast response.
- Extremely low dark count rate at cryogenic temperatures.
- Large gain.
- Compatibility with magnetic fields.

courtesy of the NEXT Collaboration
ONE VOLUME

- One individual volume: lower cost, no cracks, continuously purified.
- Uniform response all over the place.
- Charge sharing among sensors allows for 3D reconstruction.
FEATURES OF LIQUID XENON

A FULL BODY PET OF LIQUID XENON

- 2-m axial length.
- 6x6 mm² SiPMs on the external surface.
- Typical p.d.e. for VUV Hamamatsu SiPMs: ~25%.
- Non-reflective internal surface to improve spatial resolution.
OTHER CHARACTERISTICS

- Scintillation yield: \(~30\,000\) photons at 511 keV.
- Scintillation peak: \(178\) nm -> VUV-sensitive SiPMs or wavelength shifter.
- Attenuation length@511 keV: \(3.6\) cm -> adequate thickness.
- Photo-fraction: \(22\%\).
- Low temperature needed: \(161\) K.
INTRINSIC ENERGY RESOLUTION

\[ R^2 = R_{\text{geom}}^2 + R_{\text{stat}}^2 + R_{\text{recomb}}^2 + R_{\text{intr}}^2 \]

\[ \sim 6\% \sigma \text{ @zero E field, 511 keV} \]

- Energy resolution dominated by non-proportionality of LXe scintillation light and recombination.

[T. Doke, et al, Japan J. Appl. Phys. 41 (2002) 1538]

[K.Ni, et al, JINST, vol. 1, p. P09004, 2006]
Example of realistic detector

- GEANT4 simulation models light collection fluctuation + SiPM p.d.e.
- Full-body scanner: **17-18 % FWHM total** expected energy resolution.
COINCIDENCE TIME RESOLUTION

- Scintillation decay time.
- Depth of interaction (possibly corrected by 3D reconstruction).
- Sensor response.
- Electronic jitter.

**Initial results from MC simulations in not-so-small setup: CTR below 150 ps.**

**On going simulation studies to understand the different contributions in a realistic scanner.**

[JJ.Gómez Cadenas et al., JINST, vol. 1, p. P09004, 2016]
MLEM ALGORITHM

- Adaptation of code by J. Gilliam and P. Solevi.
- Monte Carlo simulation of a phantom in the middle of a full-body scanner.
- Studies to use DNNs to identify “useful” Compton interactions.

[J. Renner et al, Processing of Compton events in PETALO readout system, Proceedings of NSS-MIC IEEE2019]
A BOX FULL OF XENON

- Aluminum CF-100 box full of liquid xenon.
- Two planes of SiPMs on opposite sides.
- Aim: measuring energy, position and time resolution with a calibration source.
- Being assembled at IFIC (Valencia).
CRYOSTAT

- Cryocooler to keep 161 K.
- Vacuum vessel to isolate xenon.
THE GAS SYSTEM

- LXe box
- Recovery tank
- Vacuum pump
- Hot getter
- Bottle for cryo-recovery
FIRST PROTOTYPE

SIPM

- VUV-sensitive (Hamamatsu and FBK) and conventional (Hamamatsu), coated with wavelength shifter.
- 2 different sizes: 3x3 or 6x6 mm².
- Four arrays of 4x4 (or 8x8) sensors, specifically designed.
- Larger area -> lower cost, better coverage, but larger capacitance -> worse ToF.

Hamamatsu VUV-sensitive S15779
• TOF-PET2 asics by PETsys for signal digitization.
• 64 channels, two thresholds separately configurable for time (low) and energy (high).
• Specifically designed for fast timing and high rate applications.
• 2 chips for the first prototype.

internal feedthrough

connector board for 4 arrays

external feedthrough

[V. Herrero-Bosch et al, PETALO read-out: A novel approach for data acquisition systems in PET applications, Proceedings of NSS-MIC IEEE2018]
STATUS

• All pieces purchased/built and being installed.

• Cooling-heating cycles and tests of thermal links to keep uniform temperature.

• Tests of cold cycles of the feedthroughs.

• Full electronic chain being tested from sensors to data processing.

• Taking data in the first months of 2021.

THANK YOU
• TOFPET asics digitize the SiPM signal.
• Front-End adapter connects TOFPET asics to data processors: asic calibration and reset, clock system control.
• Kintex Development Boards are FPGA which process data from TOFPET and send them to LDC. It controls TOFPET configuration.
• GDC order frames from LDC and builds complete events.
LIQUID XENON IN MEDICAL IMAGING

STATE OF THE ART

1976 - Lavoie, first idea of using LXe in PET

Liquid xenon scintillators for imaging of positron emitters*

Louis Lavoie

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(Received 14 March 1975)

The current understanding of xenon scintillation physics is summarized and keyed to the use of xenon as a γ-ray detector in medical radioisotope imaging systems. Liquid xenon has a short scintillation pulse (≈ 10⁻⁸ sec) and high γ-ray absorption and scintillation efficiencies. The fast pulse may facilitate imaging in vivo distributions of hot positron sources and allow recovery of additional spatial information by time-of-flight techniques. We begin by describing our own study of the feasibility of making a practical positron scanning system, and consider the problems of scintillation decay time, linearity, efficiency, purity, and electric-field amplification. The prospects for a practical instrument are considered.

1993 - Chepel - LXe TPC for Compton PET

2004 - Waseda group - scintillation only and PMTs

2007 - XEMIS - Nantes-Subatech lab - LXe TPC Compton telescope