Measurement of quasi-intrinsic energy resolution in liquid xenon for medical applications

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Abstract

One of the biggest challenges of whole-body scanners for Positron Emission Tomography is the correction of the scatter fraction, meaning the amount of false coincidences where one of the two 511-keV gammas has interacted in the patient’s body and has changed its original direction. One way to overcome this difficulty is to use the scanner energy resolution to reject the scatter coincidences, since gammas lose part of their energy in the scatter. Recently, a new concept has been proposed to use liquid xenon as a scintillation medium, instead of crystals, which are currently used in commercial scanners, and silicon photomultipliers as a read-out. In this paper we present a measurement of the quasi-intrinsic energy resolution of liquid xenon for 511-keV gammas, using only scintillation light and silicon photomultipliers with 30% photodetection efficiency. The measured energy resolution is 3.5% ± 1.2% FWHM, which improves on the current knowledge of liquid xenon properties and opens up the possibility of building scanners with unprecedented energy resolution.
1 Introduction

Positron Emission Tomography (PET) is a non-invasive technique which images the metabolic activity of organs or tissues. It is based on the injection of a radiotracer (for instance, $^{18}$F fluorodeoxyglucose) into the patient. The radioisotope decays via $\beta^+$, emitting a positron which annihilates with one of the electrons of the body. The two 511-keV gammas originated from the annihilation propagate in an almost back-to-back direction and convert in a ring of detectors (usually scintillators). The determination of the gamma conversion points allows one to reconstruct the line where the photons have been created (Line Of Response, or LOR). The accumulation of a large number of LORs provides the image of the area of emission of the gammas, through image reconstruction algorithms.

The sensitivity of a PET scanner increases with the axial field of view, which allows, on the one hand, imaging a larger part of the human body in the same exposition, and, on the other, using more LORs to reconstruct a given image. The increased acceptance of PETs with large axial field of view (LAFOV PET) results in sensitivities 10 to 40 times larger than those of conventional PETs [3].

However, LAFOV PETs present some new challenges. One of the most important is the handling of large-angle LORs. Indeed, most of the increase in sensitivity of large-acceptance systems arises from recording LORs which form large angles with respect to the radial coordinate. The path length inside the patient’s body of the photons defining such LORs is larger than in conventional PETs, where the predominant emission angles are small with respect to the radial coordinate. In consequence, absorption and scattering becomes increasingly more important.

Although both effects can be corrected, modelling absorption is relatively straightforward while the treatment of multiple scattering is difficult to implement. Analytical models typically deal only with single scatters—which is unrealistic for large LORs—and the use of Monte Carlo simulations introduce unwanted dependences with the patient size and the setup [13]. The difficulty to treat scatter properly in LAFOV PETs, then, negates partly the increased sensitivity.

An obvious handle to suppress the contribution of scatters is to take advantage of the fact that scattered gammas loose part of their energy:

$$E_{\text{scat}} = \frac{E}{1 + \alpha(1 - \cos \theta)},$$

(1)

where $E$ is the initial energy, $\theta$ is the scattered angle, and $\alpha = E/511\text{keV}$. Therefore, if the scanner has a good energy resolution, it is possible to reject a large fraction of scatter coincidences using a narrower energy window to accept them. Commercial PET scanners use scintillating crystals as a detection medium, such as LYSO or LSO, which can achieve energy resolutions
of 10 – 12% FWHM at 511 keV \[18\]. In current detectors this will typically lead to scatter fractions in the range of 30 – 40\% \[18\], which would worsen in the case of a whole-body PET.

In Ref. \[16\], a LAFOV PET based in liquid xenon (LXe) was proposed and its performance studied in detail. The proposed system, named PETALO, used exclusively the copious scintillation light produced in LXe by ionising particles (~30000 photons at 511 keV), readout by a shell of VUV-sensitivity SiPMs surrounding the active volume \[10\] \[11\] \[14\]. With respect to pioneer work in the field \[3\] \[6\] \[8\], PETALO offers the advantage of using SiPMs, which have high gain and fast response, as well as the advantage of presenting virtually zero dark current at the cryogenic temperatures of liquid xenon. SiPMs sensitive to the VUV scintillation light of xenon are now available commercially, therefore they can be used directly without wavelength shifters. Detecting exclusively the scintillation light, rather than scintillation and ionisation (as in Ref. \[9\] \[14\]) simplifies considerably the design of the scanner and reduces its complexity and cost.

On the other hand, pioneer work on liquid xenon detectors reading only scintillation light obtained mediocre energy resolution results. Thus, Doke and collaborators obtained 26% FWHM \[8\], while Ni and collaborators found a better, but still rather mediocre value of 19% FWHM \[15\]. These results do not agree with modern Monte Carlo simulations, which predict a much better energy resolution for a LXe apparatus reading scintillation charge, as we will discuss later on in this work.

In this paper we present the first measurement of the quasi-intrinsic energy resolution of liquid xenon for 511 keV gammas, obtained only from scintillation light with an optimised setup based in VUV SiPMs. We obtain a result much better than those previously reported, i.e., \(3.5\% \pm 1.2\%\) FWHM at 511 keV. This result reinforces the interest of PETALO as a new type of LAFOV PET, with unprecedented energy resolution.

2 Experimental setup

A first prototype of the PETALO concept (PETIt) has been built and operates at the Instituto de Física Corpuscular in Valencia, Spain. It consists of an aluminum cube, of 18 cm internal size, filled with liquid xenon and kept in a larger vacuum vessel for thermal isolation (Fig. 1). The xenon is continuously recirculated in gas phase by a double diaphragm compressor and is purified by passing through a hot getter to remove impurities such as nitrogen, water and oxygen, which can quench xenon scintillation light \[4\]. The cube is cooled directly by a CH-110 cold head from Sumitomo via a set of custom-made copper thermal links. The cold head can reach a temperature of -240 °C using a HC-4E helium compressor. The gas enters and exits the cube through a heat exchanger, where the cold gas on the way out
contributes to the initial cooling of the warm gas on the way in, maximizing the cooling efficiency. The LXe temperature and pressure of operation are -109 °C and 1.26 bar respectively.

Figure 1: Bottom view of the liquid xenon aluminum cube inside the vacuum vessel.

Figure 2: Left: teflon block used to enhance light collection. Right: instrumented plane of four arrays of 4×4 SiPMs.

Two sets of VUV-sensitive SiPMs face the xenon on opposite sides of the cube and detect the scintillation light. The space in front of the SiPMs is filled with two polytetrafluoroethylene (PTFE) blocks, with 5-mm deep holes in front of each SiPM (Fig. 2–left). The xy size of the holes matches that of the active area of the sensors almost perfectly. When filling the cube with xenon, the liquid pervades the holes, and the result is that each SiPM is exposed to the scintillation light of gamma interactions occurring only in the hole in front of it. Since PTFE is highly reflective to VUV light
we obtain a very large geometric collection efficiency of the scintillation light. The aim of this setup is to measure the energy resolution of liquid xenon as a PET scintillating medium, compared to conventional crystals, which are small units, usually coupled to SiPMs one-to-one, and have reflectors on the walls to maximise light collection. Our setup mimics a conventional one made of crystals, with liquid xenon replacing LSO or LYSO.

The SiPMs are Hamamatsu devices, model S15779(ES1), and they are sensitive to VUV light, with a photodetection efficiency of around 30% at the xenon scintillation peak. They have an active area of $5.95 \times 5.85 \text{ mm}^2$ and are packed in arrays of $4 \times 4$ sensors, with a pitch of 7.5 mm and a protective quartz window in front, with a transparency larger than 90% to VUV light. Four SiPM arrays are arranged to form a 64-sensor instrumented plane (Fig. 2–right); two of these planes are installed on two opposite sides of the cube.

An aluminum port is inserted in the middle of the cube and hosts a carbone fibre tube containing a $^{22}$Na calibration source, which provides two almost back-to-back gammas of 511 keV. When a gamma interacts in xenon, either through Compton or photoelectric process, it produces scintillation light which propagates isotropically in the hole, gets reflected on PTFE and eventually reaches the SiPM in front of the hole, where a fraction of it gets detected, according to the photodetection efficiency of the sensor. Photon losses can come from the PTFE non-perfect reflectivity and the small distance ($\sim 1 \text{ mm}$) present between the SiPM plane and the teflon block. Two TOFPET2 ASICs [7, 12], one for each SiPM plane, integrate the detected charge and provide a fast timestamp, which is used for TOF measurements. They are placed in vacuum just behind the aluminum wall of the cube, to reduce the degradation of the signal before digitisation. After digitisation, the signal goes through the acquisition system, which is made of two boards: a front-end adapter reads the signal from the ASICs and sends it to the processor, which distributes configuration and data between the computer and the ASICs as well as manages clock synchronisation.

3 Measurements

A $^{22}$Na source with $\sim 330 \text{ kBq}$ of activity is placed in the calibration port of PETit. The radioactive material is a sphere of 0.25 mm of diameter, therefore can be considered point-like, and it is encapsulated in a plastic support. The source is inserted in the port in such a way that its final position is half way between the two instrumented planes ($z$ direction) and in the (0, -0.9 mm) position in the $xy$ plane, where $y$ is the vertical direction. During a run, a timestamp is provided by the ASIC whenever the recorded charge passes a given, low, threshold in a channel; if the charge exceeds a
second, higher threshold, the ASIC starts integrating it, until it goes below
the threshold again. If the second threshold is not reached, the integrated
charge is not saved. Four buffers are available per channel, where analog
values related to time and charge of the input signal are stored before being
digitised. Therefore incoming groups of electrons can be integrated and time
tagged while carrying out digitisation operations, thus reducing dead time
to a large extent. The output of the data acquisition is a list of channels
with an integrated charge and a timestamp.

Once the channels are divided event by event, a first filter is applied
to retain only coincidences, i.e., events where at least one sensor from each
sensor plane is present. The following step consists in singling out the sensor
with larger detected charge for each plane: due to the use of teflon blocks,
it is always the sensor coupled to the xenon volume where the interaction
happened, and it detects most of the total light of an event.

An example of distribution of the charge detected by these sensors is
shown in Fig. 3, which shows the photoelectric peak, together with the
Compton shoulder. The position of the peak varies with the sensor, due to
differences in gain, therefore all the channels need to be equalised to one
reference value. This is done fitting the charge distribution to a gaussian
+ polynomial function and extracting the best value for the mean of the
gaussian function. The average of the means of all the channels is chosen to
be the reference value for the equalisation.

After the equalization of the channels, the same fit to a gaussian+polynomial
function is performed to the charge detected by the sensors belonging to each
plane separately (Fig. 4). An energy resolution of $3.5\% \pm 1.23\%$ (sys.) FWHM
is found for 511-keV gammas in the sensors. The error of the measurement

![Figure 3: Example of distribution of the charge detected by one channel
fitted to a gaussian+polynomial function. The range has been chosen to
highlight the photoelectric peak, compared with low energy events.](image)
Figure 4: SiPMs charge distribution on a SiPM plane. A gaussian+polynomial fit is applied to extract a measurement of the energy resolution.

has been estimated varying the range and the binning of the fit, as well as the function we fit to (a simple gaussian or a gaussian+polynomial). The central value of the measurement corresponds to the average between the lowest and maximum value.

4 Discussion

In this paper we have presented a measurement of the energy resolution of a LXe system, where scintillation light is read out by high-PDE (30%) SiPMs. The geometrical acceptance of our setup, in which all the scintillation light produced by a given gamma interaction is efficiently collected into a channel of \( \sim 6 \times 6 \text{ mm}^2 \), and readout by a single SiPM, is excellent, of the order of 53% and much higher than that obtained by previous works which in turn measured a worse energy resolution \[8, 15\].

Our result is compatible (although better) than the Monte Carlo predictions based in the NEST software [17]. We have used a software application based on GEANT4 [1] and the GEANT4 integration of NEST to simulate the excitation, ionization and scintillation of liquid xenon. The physical and optical properties of the materials in use are simulated in detail, in particular the reflectivity of PTFE, which has been modelled as a Lambertian reflectivity with a value of 98%. The other physical parameters relevant for gammas and optical photon propagation are collected in Table 1. The photodetection efficiency provided by the sensors datasheet is included as a function of the wavelength of the optical photons and a charge fluctuation of 15% is applied on the single photoelectron to mimic the charge fluctuation of SiPMs. The effect of dark current at LXe temperatures is negligible. The same filters
| Parameter                                      | Value       |
|-----------------------------------------------|-------------|
| Density                                       | 2.94 g/cm³  |
| Attenuation length for 511 keV gammas         | 3.7 cm      |
| Average scintillation wavelength              | 178 nm      |
| Rayleigh scattering length                    | 36 cm       |
| Transparency of quartz windows in front of SiPMs | 0.9        |

Table 1: Summary of the LXe relevant properties used in the simulation.

described in Sec. 3 are applied on simulated data, event by event, namely, both planes must have at least one sensor with detected charge, and the SiPM with largest charge is retained for the analysis.

![SiPM charge distribution in Monte Carlo](image)

Figure 5: SiPM charge distribution in Monte Carlo.

The energy resolution provided by the Monte Carlo simulation is $4.9\% \pm 1.9\%$ FWHM, much better than what was obtained by previous measurements, but still not as good as that measured by our setup, although compatible within errors. A possible explanation for this is the fact that NEST was conceived as a software to simulate the physics of the interactions of gammas in LXe in the presence of an electric field, as it is always the case in dual-phase dark matter time projection chambers which have been so far its application domain. The effect of even a tiny electric field (as the one we have used, to approximate the “zero field” case), may introduce a small energy resolution degradation, which may explain the difference between data and Monte Carlo simulations.
5 Conclusions

We have measured the energy resolution of the liquid xenon response to 511-keV gammas, finding a result as low as $3.5\% \pm 1.2\%\text{(sys.)}$ FWHM. Due to the large light collection of the system, this can be considered a measurement of the quasi-intrinsic LXe energy resolution at this energy (for a fixed photodetection efficiency of the sensors).

Our results improves dramatically that obtained by previous measurements, to the best of our knowledge, while being in reasonable accord with the Monte Carlo. It opens, therefore, a new scenario for the application of liquid xenon in the PET technology, since it lowers the limit on the best resolution achievable (for the scintillating crystals commonly used in the field the measured energy resolution is around 10–12% FWHM). The huge improvement that LXe offers can in principle allow for the rejection of a much larger number of scatter coincidences and a large boost to the overall performance in LAFOV scanners.

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