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Compton imaging with liquid xenon and ^{44}SC: recent progress toward 3 gamma imaging

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Abstract

BACKGROUND: Subatech has initiated research works in view of qualifying a new medical imaging technique, thanks to the presence of the Arronax cyclotron, which is located in the outskirts of Nantes, France. This new technique is called 3γ imaging.

MATERIAL AND METHODS: The main idea is to detect the three γ-rays emitted indirectly or directly by specified radionuclide (Sc^{44}) and reconstruct its position in three-dimension in real time, with a spatial resolution around one centimeter. To make a γ-ray detector with high sensitivity, good spatial resolution and homogeneous volume, ultra-pure liquid xenon is a good choice to be selected as a detector media due to its excellent properties for particle detection (liquid, high atomic number, high density, high stopping power).

RESULTS: XEMIS (Xenon Medical Imaging System), which is a prototype of high sensitive liquid xenon Compton telescope, is used to demonstrate this 3 γ imaging. With an ultra-low noise front-end electronics operating at liquid xenon temperature (around 100 electrons NEC) and a fast UV sensitive PMT, high spatial resolution in three-dimension and high energy resolution are achievable. This is particularly important for Compton imaging since all interactions in the medium have to be identified to reconstruct the direction of incident γ-ray.

A prototype with an active area of 1’’x1’’ is now in test at Subatech and shows promising results with a 511keV source from ^{22}Na. All the cryogenic system is fully operational with a high purification rate and shows a very good stability.

CONCLUSIONS: A new geometry XEMIS2 is currently under development to adapt this imaging technique to the small animal size.

Key words: 3 gamma imaging, Liquid Xenon, Medical instrumentation, Sc44

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Background

The 3 γ imaging is a new concept of medical imaging developed at Subatech with the aim to achieve direct 3D reconstruction of the emission position of a 3 γ emitter radionuclide, in particular the ^{44}Sc. This radionuclide emits a γ+ (E_{mean} = 632 keV, E_{max} = 1473 keV) and in quasi coincidence a gamma ray (E = 1.157 MeV) in 99.9% of the disintegration 1. The two back-to-back 511 keV photons from the positron annihilation are detected by a classical PET device giving a line of response (LOR). The third γ ray is then detected and located by a Compton camera. The use of this particular detection system is mandatory to be able to reconstruct with a good precision the arrival path of the gamma ray. The principle of a Compton camera is to locate the vertices of Compton interactions of the γ-ray into the matter. By knowing the 3D position and the energy of the Compton interactions, the sequence of the interactions can be reconstructed thanks to the following equation:

$$\mathrm{Cos}\,\theta = 1 - m_e c^2 \frac{E_1}{E_0 E_0 - E_1}$$

where θ is the scattering angle, $m_e c^2$ the mass of the electron (511 keV), E0 is the energy deposited at the first hit (1157 keV) and E1 is the energy deposited at the second hit. Since in dense medium the direction recoil of the scattered electron is generally not measurable, a revolution symmetry appears. This leads to the reconstruction of a cone of presence containing the incident γ-ray and not a straight line. This reconstructed cone is determined by 3 parameters: the apex (3D position of the first hit), the aperture angle (θ determined by the energy deposited at the first hit) and the

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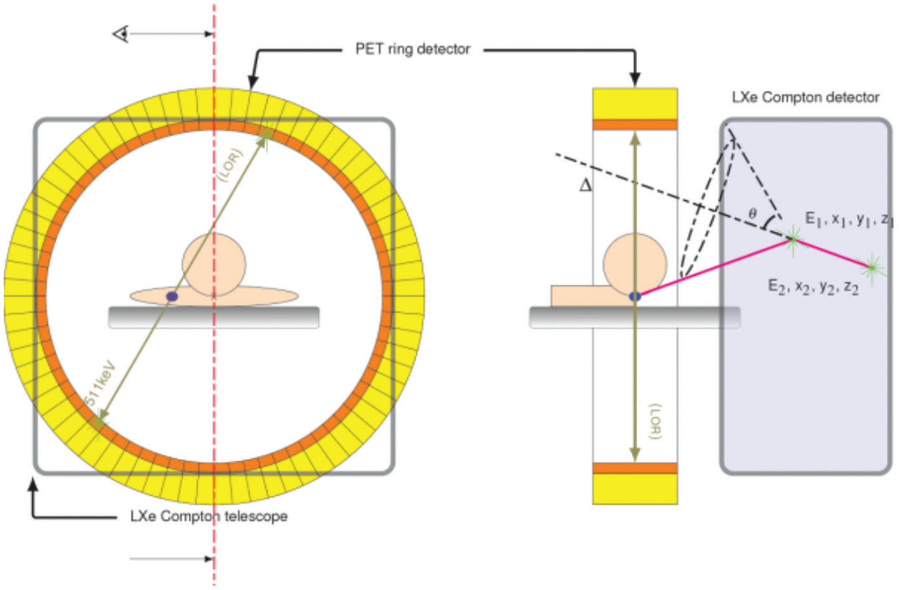

Figure 1. Principle of 3 γ imaging

axis Δ (given by the vector between the first and the second hit). The 3D position of the radionuclide can be thus reconstructed by locating the intersection point between the LOR and the cone. In order to take advantage of this technique the Compton telescope must have some important features in particular given by a good spatial and energy resolution, a high efficiency and a fast time of response. Figure 1 shows the principle of the 3γ imaging technique.

The use of liquid Xenon (LXe) to build the Compton Camera is particularly relevant 2. Firstly, LXe is a dense medium (3 g/cm^3) which is very useful to have a high stopping power for γ rays. Around 84% of 1.157 MeV gamma rays could be detected with a 12 cm length volume. Secondly, LXe has a high scintillation (~16 000 UV photons/MeV) and ionization yield (~54 400 electrons/MeV) at a 2 kV/cm electric field and finally, the use LXe gives the advantage to have a monolithic and homogeneous active volume.

In order to understand the performance of the 3 γ imaging using a LXe Compton telescope, we first performed GEANT4 simulations with three major hypotheses concerning the Compton telescope: a 500 μm spatial resolution in each direction, an energy resolution where E mis the energy deposit in MeV, and a front-end electronics with 200 electrons (~10 keV) noise level. The result of simulations for small animal geometry shows that a spatial resolution of ~1 cm can be achieved with 3 γ imaging for each event without any iterative algorithmic reconstruction 3.

The Xenon Medical Imaging System (XEMIS)

XEMIS is composed of 5 different major parts: the storage and recovering, the cold-head, the purification loop, the rescue system and the cryostat containing the Compton camera (Figure 1).

A Pulse Tube Refrigerator (PTR) which is specially designed and optimized for xenon liquefaction 4 is selected to be the cold-head of XEMIS. It is used to provide stable cooling power up to 200 W at 165 K. An electrical heater up to 180W is assembled between the copper cold head and PTR in order to adjust the net-cooling power by compensating the extra cooling power from the PTR. All this liquefaction part is connected to the cryostat and is maintained at a distance of 2 meters for the purpose of reducing mechanical noise due to the vibration of the PTR.

A recirculation system driven by an oil-free membrane pump is used to purify xenon continuously in order to reduce the electronegative contamination (O_2, CO_2, N_2 etc.) from outgassing. These impurities have to be removed as much as possible because the ionizing electrons created by the interaction of   rays can be captured by electronegative molecules instead of drifting toward the anode. Two rare-gas purifiers (SAES PS4-MT3-R/N getter) connected in parallel are used to purify the gaseous xenon. Since the getters can only purify gaseous xenon, the liquid xenon must be evaporated to gaseous state before entering purification loop. Therefore, a 22.5 m coaxial heat exchanger made of stainless steel is placed 50 cm above the cryostat. This system is used to recuperate the vapor heat to liquefy the xenon after purification. This heat exchanger is designed to have 95% of efficiency up to 50 NL/min (4.92 g/s) 5.

The storage and recovering system of the Xenon is made of classical commercial gas bottle B50 at the time being. A 4 m^3 stainless steel tank is connected to the cryostat in case of recuperation in emergency.

The Compton camera in the cryostat is composed of a Time Projection Chamber (TPC) immersed in a vessel filled with LXe. When a γ ray interacts inside the TPC, the energy deposit creates proportional scintillation (VUV photons of 178 nm) and ionization signals. By applying an external low electric field (E_{drift})adjustable up to 2 kV/cm provided by 24 copper field rings connected to each other by 500 MΩ resistors, ionizing electrons will drift toward the anode with constant velocity and can then be collected.

The active volume of the TPC is 2.54 × 2.54 cm^2 (X-Y plane) with 12 cm length (Z direction). The anode is placed on the bottom part of the TPC and is segmented into 4 × 4 square pixels. Each pixel has a size of 6.35 × 6.35 mm^2. This anode is connected to an ultra-low noise front-end readout electronics based on the IDeF-X v1.0 ASIC chip 6 which has around 100 electrons NEC

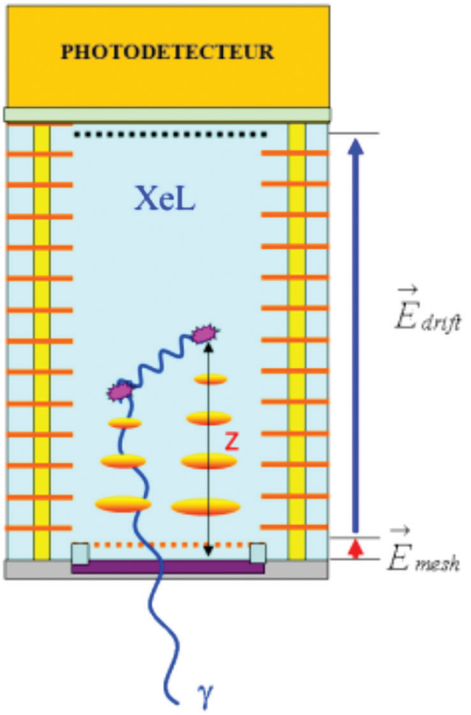

Figure 2. TPC principle

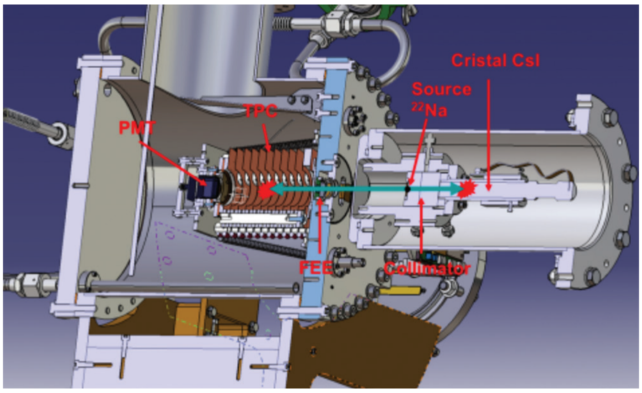

Figure 3. Presentation of the setup

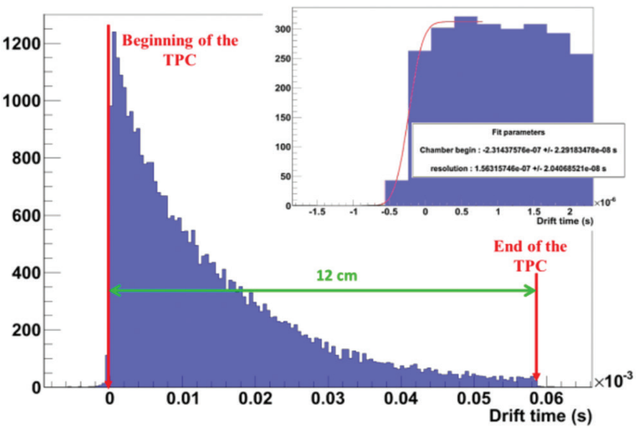

Figure 4. Drift time measurement and drift time resolution

at LXe temperature. A 670 lpi (line per inch) micromesh made of a 5 μm thick copper foil is placed 200 μm above the anode and is used as a Frisch grid. In this space, an electric field (Emesh) with a strength upper than 50 times the electric field present in the drift space must be appliedto ensure a 100% electron transparency. A Hamamatsu R7600-06MOD-SSY99 photomultiplier tube (PMT), placed at the other side of the TPC, is used to detect VUV scintillation signals. The Figure 2 presents a sketch of the TPC principle.

Results

In order to demonstrate the potentiality of such kind of detector to be used as a Compton camera, Subatech developed a setup based on ^{22}Na source (β+γ emitter E_{mean} = 545 keV, E_{max} = 1257 keV and a 1274 keV γ-ray in 99.9% of disintegration) placed outside the TPC at 12.5 cm distance from the anode. A CsI crystal coupled with a PMT is placed behind the source in order to trigger the TPC on the two back-to-back 511 keV γ-ray. The waveforms of the electric signals (anode composed of 16 pixels) and scintillation signals (PMT) are recorded with a V1740 Caen DAQ system and a V1720 Caen DAQ system, respectively. Figure 3 presents a sketch of the setup.

With this TPC, the X and Y position are given by the relative signal present on each pixel of the anode. This 16 pixels segmentation allows a spatial resolution of 1.5 mm in each X and Y direction. A 64 pixels segmented anode, which allows 500 μm spatial resolution in X-Y plane to ensure a good Compton reconstruction, will be used in the future. The Z position is simply determined by measuring the time difference between the PMT signal, which indicates the interaction time, and the collection time on the anode of electrons created by the Compton interaction. This time difference multiplied by the drift velocity gives the Z value. The drift velocity of the charge carriers is extracted from the data by calculating the time difference between the beginning and the end of the TPC as presented in Figure 4. According to our measurement, the resolution in the Z-direction can be estimated at 350 μm 7. The energy deposited at the interaction point is determined by measuring the amplitude of the produced signal on the anode. The intrinsic energy resolution of 511 keV energy deposit in LXe is obtained as around 6%. With the TPC all the parameters needed (X, Y, Z, E) to reconstruct the Compton sequence are accessible.

Future

A first work has been initiated with the open GATE collaboration 8 to implement the Xenon as a medium in GATE in order to be able to quantify and share the benefit of this new imaging technique. XEMIS2, presented in Figure 5, is a new geometry able to achieve a full 3 γ imaging with liquid Xenon. The aim of this new instrumental development is to detect both the β+ disintegration and the third γ raywith only one device. This geometry takes the shape of a hollow cylinder of 24 cm length designed for small animal imaging containing two different readout planes on the top and the bottom part of the cylinder. Each plane is equipped with a thin micromesh Frisch Grid and contains an anode segmented in pixel of 3.175 × 3.175 mm². The anode will be connected to 200 Front-End electronics read-

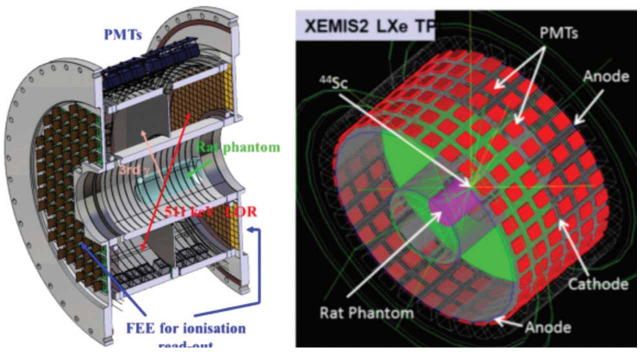

Figure 5. Xemis2: The full three gamma imaging principle

out cards of 64 channels each. There will be a total amount of 25 600 electronic channels. This new geometry will hold around 130 kg of LXe. A new concept of REcovery and STOrage system for Xenon (ReStoX) is developed by Subatech and AirLiquide9, which is designed to be able to store xenon at a temperature between −108°C (liquid phase) and 20°C. XEMIS2 will be equipped with a small ReStoX system to ensure a rapid filling and recovering of the Xenon. The inner radius of the camera is 8 cm and the outer radius is 20 cm giving a depth volume of 12 cm for an orthogonal incident γ ray. The UV-light produced by the interaction of γ rays is collected by an assembly of 192 Hamamatsu PMT. By a particular trigger system on the scintillation light, it is possible to read only pixels that are susceptible to contain information in order to reduce the flow of data and to be able to follow the rate.

Conclusion

A new concept of medical imaging technique is starting with the construction of XEMIS. This liquid Xenon Compton camera prototype shows very promising results with 511 keV γ rays. This leads to the XEMIS2 development and construction which is a fully dedicated system for 3 γ imaging containing 130 kg of liquid Xenon.

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