PROCEEDINGS OF SCIENCE

Dark Matter Search Application to Medical Physics: The 3DΠ Project.

M. Lai,[a,b,*] **A. Ramirez,**[c] **X.Li,**[d,i] **A. Renshaw,**[c] **M. Wada,**[e] **A. Zabihi,**[e] **D. Franco,**[f] **F. Gabriele,**[b] **C. Galbiati**[d,h] **and H. Wang**[g]

[a] *Physics Department, Università degli Studi di Cagliari, Cagliari 09042, Italy*
[b] *INFN Cagliari, Cagliari 09042, Italy*
[c] *Department of Physics, University of Houston, Houston, TX 77204, USA*
[d] *Physics Department, Princeton University, Princeton, NJ 08544, USA*
[e] *AstroCeNT, Nicolaus Copernicus Astronomical Center, 00-614 Warsaw, Poland*
[f] *APC, Université de Paris, CNRS, Astroparticule et Cosmologie, Paris F-75013, France*
[g] *Physics and Astronomy Department, University of California, Los Angeles, CA 90095, USA*
[h] *Gran Sasso Science Institute, L'Aquila 67100, Italy*
[i] *Lawrence Berkeley National Laboratory, Berkeley, CA 94720, Stati Uniti*

E-mail: michela.lai@ca.infn.it, arenshaw@uh.edu, masayuki@camk.edu.pl, aramir52@cougarnet.uh.edu, xinranli@lbl.gov, azabihi@camk.edu.pl

3DΠ will be the first total-body scanner for Positron Emission Tomography (PET) using liquid Argon as a scintillator medium. The project is an application in medical physics of the ongoing R&D of the DarkSide collaboration, whose main aim is the direct detection of dark matter particles via liquid Argon targets. Utilizing liquid Argon as a scintillator will allow for a competitive and cost-effective total-body PET scanner to be built, thanks to the high availability of atmospheric Argon that can be isotopically distilled as needed, along with potential for the availability of underground Argon. The preliminary results here demonstrate that, while the spatial resolution is comparable to that of commercial scanners, the 3DΠ scanner is expected to show outstanding detection sensitivity, allowing for a reduction of the PET scanning time or a reduction of the patient dose.

**** The European Physical Society Conference on High Energy Physics (EPS-HEP2021), ****
**** 26-30 July 2021 ****
**** Online conference, jointly organized by Universität Hamburg and the research center DESY ****

[*]Speaker

PoS(EPS-HEP2021)778

1. Introduction

Positron Emission Tomography (PET) is a non-invasive technique for the diagnosis of cancer and brain diseases. The patient is dosed with a positron-emitting radiotracer, which accumulates in diseased regions of the body, where the metabolism is higher. The emitted positron annihilates with local electrons, producing two gammas with an angular separation near 180^o at 511 keV. The gammas are then observed by an annular array of photosensors, surrounding the bed hosting the patient. The photosensors are inserted in a coincidence circuit: the event is triggered only if both gammas are detected within the same time coincidence window. The line connecting the two fired photosensors is the Line of Response (LOR). In traditional PET scanners, the probability of reconstructing the interaction vertex is uniform along the LOR. A strong improvement of the scanner's performance can be achieved through the addition of time-of-flight (TOF) information of the incident gammas: the position PDF is then the mean value of a gaussian centered in the interaction vertex. This increases the signal-to-noise ratio (SNR), providing an increase of the spatial resolution and subsequently, the sensitivity of the scanner. Current, traditional PET scanners use crystals as scintillators: the gamma enters the crystal, whose scintillation light is observed by photomultipliers tubes (PMTs) [1], or in more recent times by silicon photomultipliers (SiPMs) [2] [3].
The DarkSide collaboration's first aim is the detection of dark matter particles in ultra-pure liquid Argon. The first detector, DarkSide-50, using 50 kg of liquid Argon, set an outstanding exclusion limit for WIMPs, dark matter particles assumed to have masses in the range 1 GeV/c^2 - 100 TeV/c^2 and weakly interacting with baryonic matter [4, 5]. The next steps of the DarkSide program consist of the building of multi-tonnes liquid-Argon detectors, to further search for even more elusive WIMPs. In order to do this, extraordinary efforts have been applied to reduce the backgrounds in the detector, mainly focused on the choice of the photosensors and the Argon target. The PMTs will be exchanged for SiPMs, which are more radiopure and also cheaper in mass-scale production. The Argon will be extracted from underground sources, greatly reducing the radioactive isotope ^{39}Ar, thus providing a reduced background rate. The 3DΠ project is a medical physics application of the DarkSide program's resulting technology: a total-body TOF-PET looking at the scintillation and Cherenkov light produced in liquid Argon, via a wide set of custom-developed SiPMs [6].

2. The Geometry

The ongoing R&D of the 3DΠ scanner is based on a GEANT4 simulation, which allows for optimization of the system geometry. Based on current simulations, the 3DΠ scanner will have an axial length of 2 m, an inner radius of 45 cm, and an outer radius of 64 cm. The outer and inner surfaces, as well as the end-caps, are 4 mm sheets of titanium, which form the cryostat and enclose 9 layers of PTFE, each containing two arrays of SiPMs, as shown in Figure 1(left side). The arrays are set normal to the radial direction, on each side of the surfaces of the PTFE volumes. This layer-focused geometry of the scanner is done to optimize the signal-to-noise ratio. Further tuning is ongoing, to reduce the number of channels and therefore the build cost of the scanner.

The scintillation light from liquid Argon peaks at 128 nm, while the usual PMT or SiPM photodetection efficiency peak is around at 420 nm. This is why tetraphenyl butadiene (TPB) was evaporated onto the inner surfaces of DarkSide-50, in front of the photosensors. In fact, the TPB shifts the emission peak from 128 nm to 420 nm, with a negligible loss of the intensity of the radiation [7]. The same technique can be applied as well in the 3DΠ scanner. Alternatively, the liquid Argon can be doped with about 0.5 % of liquid Xenon. This shifts the average emission from 420 nm to 178 nm. Custom-developed SiPMs, sensitive to near-ultraviolet light, have been developed from Fondazione Bruno Kessler (FBK) and have been used for the base-lining of the 3DΠ design. While the first scintillation option is the most intuitive, and used most frequently in dark matter searches, the second one is more interesting in the context of medical physics. With Xenon doping, the scanner's event reconstruction algorithm would circumvent a time delay of about 1 ns due to the scintillation of the TPB. Furthermore, the addition of the Xenon also positively affects the time response of the scintillation process [8, 9].

PoS(EPS-HEP2021)778

The expected signal from a patient is back-to-back 511 keV gamma particles. A gamma scattering in liquid Argon has a probability of 70% to excite the triplet state, which is forbidden at dipole momentum and hence yields a significantly long average time-decay of 1.6 us; this can be compared with the remaining 30% of Argon excimers, which are excited into the allowed singlet state that has an average time decay of only 6 ns. While for dark matter searches this is the key to distinguish most of the local backgrounds from a potential dark matter signal [5, 10], in the case of a PET scanner this widens the trigger circuit coincidence window, decreasing the signal-to-noise ratio. Furthermore, the increase of the coincidence circuit time window also increases the dead-time of the acquisition; thus affecting the sensitivity of the scanner. As a solution, the presented design also assumes the replacement of the TPB with the addition of 0.5 % of Xenon into the liquid Argon, since it then shifts the average triplet state time decay down to about 100 ns, resulting in an overall scintillation time comparable with the ones observed in traditional scintillating crystals.

3. First Results From Quality Checks

The performance of the 3DΠ scanner has been tested according to NEMA-NU-2018 [11] document, which provides experimental tests to benchmark the performance of a PET scanner as well as standards to adhere. The preliminary results come from tests based on the GEANT4 simulation of the 3DΠ scanner.

The sensitivity of a PET scanner is defined as the number of detected counts per unit time and per unit of activity of the source. A line source was simulated, completely wrapped in an attenuating sleeve of aluminum with varying thickness. This allows for fitting the count rate as a function of sleeve thickness; the limit for null thickness is the sensitivity, which was evaluated to be 505 cps/kBq for the design of the 3DΠ scanner using liquid Argon and TPB. A slight increase to 513 cps/kBq is observed for the second possible design, with Xenon doped liquid Argon and the absence of TPB. In both cases, the detector shows an outstanding sensitivity, approximately one order of magnitude higher than that achieved by average commercial technologies.

The spatial resolution is evaluated by setting a point-like source in six different positions within a water phantom, in order to report the spatial resolution along both the axial direction and the radial one. While the Argon-only design shows on average a spatial resolution of about 10 mm, the Argon plus Xenon design shows an improvement, reducing down to about 5 mm in each direction, which is comparable with the spatial resolution from commercial scanners. The resolution has been evaluated after reconstructing the image with the filtered back-projection, although an improvement of the spatial resolution is expected by using an interactive algorithm for the image reconstruction. On the other hand, the contribution to the spatial resolution due to the time resolution shows to be very promising, estimated at about 100 ps from a preliminary evaluation.

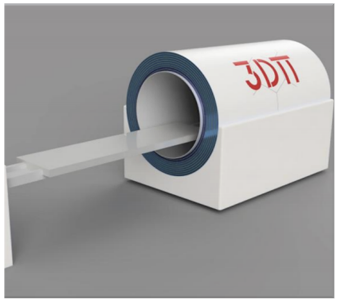
Both of these results suggest an extraordinary performance on the image quality test as specified in NEMA-NU-2018. The recommended phantom in this test is a water sphere with six radiation sources located at the same radius from the center, as shown in Figure 1 (right side) for the configuration in Argon doped with Xenon. According to the preliminary results, the quality of an image acquired in 30 minutes from commercial scanners is comparable with an image acquired by 3DΠ in only $\sim$15 s.

Thanks to the increase in sensitivity, the 3DΠ scanner provides an advantage compared to commercial scanners, since it can provide similar detailed images in much shorter times, or much more detailed images across a similar time. As an alternative, the increase in the sensitivity can instead be used to decrease the dose of the radiotracer in the patient. Patients who have previously been barred from PET scanners due to radiation safety limits, such as children and pregnant women, could then have access to PET imaging.

4. Acknowledgments

This work has been supported by the National Science Foundation (NSF) Graduate Research Fellowship under Grant No. 1746046, the University of Houston's High Performance Cluster under NSF Grant No. 1531814. Also, it was performed with the support by IRAP AstroCeNT funded by FNP from ERDF and with the support by "Fondazione CON IL SUD" Grant No. 2018-PDR-01005.

PoS(EPS-HEP2021)778



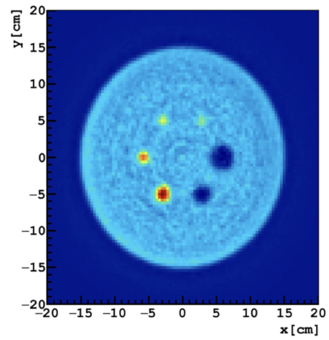


Figure 1: Left: Artist rendering of the preliminary design of the 3DΠ scanner. The scanner will have a total-body design, where the liquid Argon scintillator (in blue) will be contained in nine layers in PTFE. Each of the cylindrical layers will host two arrays of SiPMs, in order to optimize the detection efficiency. Right: preliminary image quality test on the 3DΠ scanner, for the configuration in Argon doped with Xenon. The scanner time here was ∼ 15 s, comparable with the image acquired in 30 minutes with commercial scanners.

References

[1] Badawi at al. "First Human Imaging Studies with the EXPLORER Total-Body PET Scanner", (2019),doi:10.2967/jnumed.119.226498.

[2] Jiang, Wei and Chalich, Yamn and Deen, M. Jamal, "Sensors for Positron Emission Tomography Applications", Sensors Volume 19 (2019), doi: 10.3390/s19225019.

[3] C. Romo-Luque on behalf of PETALO Collaboration, "PETALO: Time-of-Flight PET with liquid Xenon", Nuclear Instruments and Methods in Physics Research Section A, 958 (2020), doi=10.1016/j.nima.2019.162397.

[4] P. Agnes et. al (DarkSide collaboration), "Low-Mass Dark Matter Search with the DarkSide-50 Experiment", Phys. Rev. Lett. 121, 081307(2018).

[5] P. Agnes et al.(DarkSide Collaboration), "DarkSide-50 532-day dark matter search with low-radioactivity Argon", Phys. Rev. D 98, 102006.

[6] Capasso et al., "FBK VUV-sensitive Silicon Photomultipliers for cryogenic temperatures", Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 982 (2020), doi:10.1016/j.nima.2020.164478.

[7] P. Agnes et al., "First results from the DarkSide-50 dark matter experiment at Laboratori Nazionali del Gran Sasso", Physics Letters B Volume 743 (2015), doi:10.1016/j.physletb.2015.03.012.

[8] Galbiati et al., "Pulse shape study of the fast scintillation light emitted from Xenon-doped liquid Argon using silicon photomultipliers", JINT 16 (2021), doi:10.1088/1748-0221/16/02/P02015.

[9] Kubota et al., "The suppression of the slow component in Xenon-doped liquid Argon scintillation", Nuclear Instruments and Methods in Physics Research Section A, 327 (1993), doi:10.1016/0168-9002(93)91413-H.

[10] P. Adhikari et al. (DEAP collaboration), "Pulse shape discrimination against low-energy Ar-39 beta decays in liquid Argon with 4.5 tonne-years of DEAP-3600 data", Eur. Phys. J. C 81,823 (2021) doi:10.1140/epjc/s10052-021-09514-w.

[11] National Electrical Manufacturers Association (NEMA) NU 2-2018, "Performance Measurements of Positron Emission Tomographs (PET)" available at https://www.nema.org/standards/view/Performance-Measurements-of-Positron-Emission-Tomographs