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Imaging of LAr scintillation light with segmented UV photodetector coupled with Coded Mask

M. Tenti for the Nu-At-Fnal Collaboration
INFN, Sezione di Bologna - Bologna, Italy

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Summary. — Liquefied-noble-gas detectors play a crucial role in direct dark-matter search and in neutrino oscillation experiments. Liquid argon (LAr) and liquid xenon produce a large amount ($\sim 40000\,\mathrm{ph/MeV}$) of UV scintillation photons which are usually wavelength shifted before being detected. In a liquefied-noble-gas TPC, event reconstruction is based on the collection of ionisation charge while scintillation light is used for triggering and event timing, calorimetry, and particle identification. This approach suffers from limitations in rate capabilities because of the long drift times of electrons in large-volume detectors. We propose a novel approach for the full-optical imaging of scintillation light in LAr able to provide a complete 4D event reconstruction (*i.e.*, in space and time). A set of UV cameras based on the Coded Aperture technology and segmented photodetectors are employed. The new technique would allow to reconstruct with high accuracy and at high rate the path of charged tracks crossing the active volume of the detector. We present the results of preliminary Monte Carlo studies and we discuss the experimental plan aimed at fully addressing the technological challenges.

1. – Liquefied-noble-gases TPC

Liquefied noble gases, if properly purified and in the presence of a guiding electric field, are highly efficient in drifting charges (electrons, ions) generated by a crossing ionizing particle over large distances [1]. Single-phase or double-phase noble gases TPCs represent a powerful class of particle detectors, especially when large target mass, low energy threshold, good spatial resolution, and very low radioactive background are required, as in neutrino physics and dark-matter search. The liquid-argon (LAr) technology, in particular, will play a key role in particle and astroparticle physics for the next two decades; the DUNE project and the Short-Baseline Neutrino Program at Fermilab are just the two major projects taking advantage of the LAr-TPC technology.

Although noble-liquid-particle detectors usually exploit both the prompt scintillation light and the charge ionisation signals, the spatial and topological reconstruction of the event is based on the latter one only. The main limitation of relatively large TPCs comes from the slow drift of charges, which makes them not suitable to detect intense fluxes of particles. Next-generation neutrino long-baseline experiments may face this limitation with their near detectors because of the very high beam intensity.

Prompt emitted light is in the VUV region both for argon and xenon. In argon, in particular, the emission is strongly peaked at 128 nm. Lacking suitable UV photosensors with good efficiency at such a low wavelength, UV photons are converted into visible ones by means of wavelength shifters, either deposited on the detector walls or on the photosensors themselves. The prompt scintillation light is exploited for: a) providing a fast signal (at a few ns scale compared to the several milliseconds required for the collection of the charge signal) which is crucial for self-triggering applications and for off-beam background rejection; b) particle identification in combination with charge ionisation signals.

We propose a novel imaging method based on the collection of prompt scintillation light using UV sensitive photodetectors coupled to a suitable optical system.

2. – The idea

The light yield induced by charged particles in liquid argon/xenon is about 40 UV photons per keV corresponding to approximately 1000 photons each $100\,\mu$m of particles' track. Since the Rayleigh length is rather large (95 cm), high-precision imaging is possible by collecting UV light on a finely segmented focal plane. A set of optical systems arranged in stereo views can provide a fast and precise reconstruction of particles' tracks.

A toy Monte Carlo simulation has been performed in order to assess preliminarily the feasibility of the idea. Interactions with Ar nuclei of $\mathcal{O}(1\,\mathrm{GeV})$ neutrinos were generated using GENIE 2.12 [2] and the outcoming particles were propagated, using GEANT 4.10 [3-5], in a 1 meter size cubic box of LAr. Scintillation photons produced along the charged particles' tracks are propagated, ignoring Rayleigh scattering, towards the walls of the box. A set of three lenses aligned along the direction of the incoming neutrino is placed on the up, down, left and right sides of the box. The lens radius and focal length, 3.5 and 4 cm, respectively, are those typical of commercial available VUV lenses. Paraxial and thin lens approximations are used for lens simulation. Lens transmittance is not taken into account. Photons are collected at a distance of 4.4 cm from the lens on a $1 \times 1\,\mathrm{cm}^2$ focal plane with $1 \times 1\,\mathrm{mm}^2$ segmentation corresponding to the SiPM collection area. An example of a ν_μ-Ar CC simulated interaction is shown in fig. 1. An average of ~ 50 photons/SiPM strikes the array of sensors reproducing the image of the charged particle track, indicating that the idea is very promising and deserves further studies. Considering the excellent rate and timing properties of the SiPM, this technique is in principle apt to perform high-rate, high-resolution 4D images of charged tracks, opening vast fields of application.

3. – The optical system

Although UV transparent lenses do exist, their efficiency at 128 nm is low ($\leq 50\%$) and thus the reconstructed image is faint. Moreover, with any conventional optics, an acceptable focusing from the nearest plane to the farthest one requires a high depth-of-field (DOP) and consequently, extremely small apertures. We are therefore investigating an alternative solution based on optical pinholes.

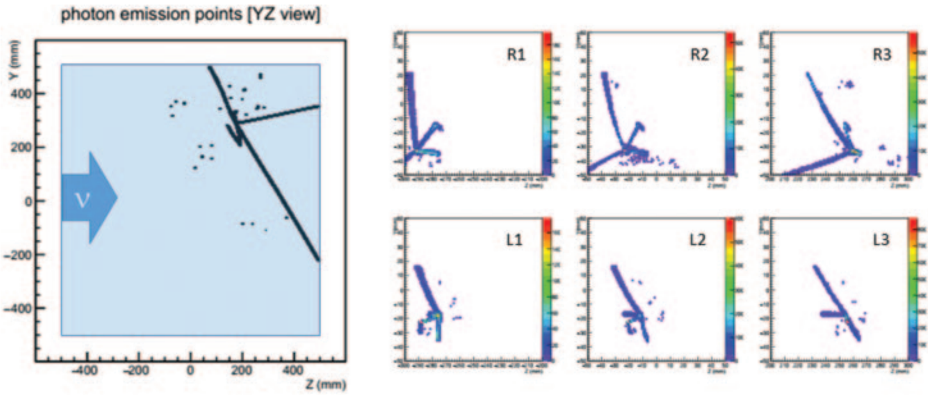

Fig. 1. – Left: the lateral view of a ν_μ-Ar CC interaction. The momentum direction of the incoming neutrino is towards positive Z coordinates. The black points are the photon emission points, while the blue area represents the LAr box volume. Right: number of photons impinging on the $1 \times 1\,\mathrm{mm}^2$ area on the lens focal plane. The labels R1, R2, R3 and L1, L2, L3 stand for the three right and left lateral lens placed on the box walls.

An optical pinhole acts as a lens by focusing light onto a plane, with, in principle, infinite DOP. The main drawback of any pinhole-based technique is its very low light collection efficiency. It has been proved that a matrix of holes of suitable size and pattern (mask) generates on the focal plane an image that can be processed to reconstruct the original one [6]. Masks with a 1:1 ratio between full and empty spaces have been developed, behaving as high-luminosity lenses (f/2) while still maintaining the property of a virtually infinite DOP. Coded Aperture Masks based on the so-called Hadamard matrices, are rather well known in astronomy and the mathematical theory of image reconstruction is well developed [7].

3˙1. *FlatCam.* – A very interesting implementation of the Coded Aperture Masks technique is the FlatCam [8]. The FlatCam consists of a coded mask placed on top of a bare sensor array with each pixel recording a linear combination of light from multiple scene elements. A computational algorithm is applied to demultiplex the recorded measurements and reconstruct the scene. The great advantage of this implementation is that the coded mask is placed extremely close to the image sensor resulting in a very thin system (~ 0.5 mm).

4. – Outlook

In order to demonstrate the power of the idea, we plan to develop a full Monte Carlo simulation of the FlatCam implementation, together with the design and construction of a small proof-of-concept prototype. Two possibilities are being considered for the UV readout system: SiPM array: the operation at cryogenic temperature will reduce the dark current by orders of magnitude with respect to that at room temperature and provide an outstanding signal-to-noise ratio for the raw (pre-processed) image; electron multiplying CCD (EMCCD) by Andor [9], whose sensor has single-photon sensitivity.

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