Boosting capabilities of liquid argon TPC detectors for low energy rare event physics

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Abstract. The groundbreaking concept proposed in this project is the construction of a prototype of a new generation liquid argon Time Projection Chamber (LAr-TPC) detector in which the electron charge generated by ionizing particles is amplified at the end of its drift path directly in the liquid argon bulk volume. If successful, the proposed research would disclose the possibility to substantially lower the energy threshold of LAr-TPC's by at least 2 orders of magnitude compared to the state of the art, making them sensitive to energy depositions of O(10 keV) and thus significantly expanding their physics potential in the search for low energy rare events.

Over the past few decades, the physics of rare events has entered a golden age primarily addressing studies of neutrino properties and searches for Dark Matter. One of the driving forces has been the realization of large mass detectors (up to the kton scale) capable of measuring energy depositions down to hundreds of keV localized in few mm^3, with uniform performances throughout active volumes as large as hundreds of m^3. Yet the controversial and mainly inconclusive results of Dark Matter searches on top of the vivid interest for a new class of low-energy phenomena such as coherent neutrino scattering, are a strong motivation for lowering the energy threshold of present detectors by orders of magnitude, to probe the keV energy scale.

One of the best-suited techniques for rare events searches is undoubtedly that of liquid argon Time Projection Chambers, which provide high granularity imaging by collecting the ionization electrons, produced by the interaction of charged particles with the target medium and drifted by a uniform electric field over a few meters.
Although the ionization energy of LAr is as low as 23.6 eV, the electron cloud gets substantially reduced (~ 50%) along the drift mainly due to recombination with positive ions and absorption on impurities, and smeared due to diffusion effects. The signal induced by the remaining charge on the sense wires at the anode is then processed by amplifiers with typical noise levels of ~1200/400 electrons for warm/cold readout electronics respectively [1]/[2]. This sets the state of the art of the energy threshold for LAr-TPC's to O(100 MeV) [3].

Clearly, a multiplication of the drifting electrons before the amplification stage of the readout electronics could dramatically improve the energy sensitivity.
Such a multiplication has been proven to be "easily" obtained for noble elements in the gas phase, with the well-established technique of Micro-Pattern Gaseous Detectors (GEMs, TGEMs, Micromegas etc.) [4]. Intense R&D activities for their implementation in LAr-TPC's have led to the design and realization of double phase detectors, in which drift electrons are extracted from the liquid to the gas phase before being collected [5].
However, besides some technical hurdles such as the difficult alignment of the electron extraction system with the liquid/gas interface, amplification obtained with this method has stability issues in time, mainly because of the abundant production of scintillation photons in the multiplication stage that easily trigger self-sustained sparks through the photoelectric effect on detector materials. Furthermore, quenching dopants can't be used to overcome this problem because, due to the temperature, they would almost entirely dissolve into the liquid with only traces remaining in gas, largely insufficient for quenching purposes. Therefore the maximum amplification compatible with steady operations is approximately a factor of 20 [6].

In this project an alternative strategy is proposed, namely pursuing controlled and stable electron proportional multiplication of the drift electrons directly in liquid argon.
Two technical approaches will be investigated in parallel.

1) Shape the anodic electrodes with sub-micrometric down to nanometric dimensions, as a scaled down version of the geometries successfully adopted in gaseous TPC's (ex: micro-strips), in order to generate a local electric field large enough (> 100 kV/cm) to trigger the proportional multiplication of charge carriers.
   Existing literature, although scarce, hints at the feasibility of this idea [7][8].
2) Focus the drift electrons towards pixel chips and accelerate them enough to enter into the silicon detector, for instance with Gas Electron Multiplier (GEM) structures. In this case the amplification stage would happen inside the chip, that could be operated in proportional amplification or in avalanche regimes in case the sensitivity to single electron count can be reached. A similar system has been recently deployed successfully for gas applications in the framework of the CYGNUS-D3 Project [9].

In case of success, the second stage of the proposal will be dedicated to the realization of a prototype detector, table-top size (~ 50 l LAr active mass), to be exposed to calibration radioactive sources and a test-beam of particles at Fermilab.

A relevant side benefit worth mentioning is that the reduction of the electrode dimension allows for higher granularity and thus improvements in spatial resolution. Actually, the detector design will benefit from a high flexibility in tuning the compromise between granularity and number of channels to be readout, depending on the specific experimental application
Eventually, such a new generation of single phase LAr-TPC detectors could revolutionize the experimental searches for low energy (< 100 keV) rare (~ 10^{-40}

cm^2) events, giving access to a broader set of information on the particles interaction such as the directionality of nuclear and electron recoils.
Additional applications are foreseen whenever very good position accuracy (< 100 μm) is a critical issue: medical imaging (as a more cost-effective and better resolution alternative to present LXe-TPC [10]), Gamma Nuclear Resonant Absorption (GNRA) radiography for security applications and telescopes for studying Gamma-ray polarization [11] are just a few examples.

The P.I. can rely on the solid expertise in the LAr-TPC technique she has gained since 2006, by contributing to the installation and commissioning of the ICARUS-T600 detector at LNGS, having been in charge of the data taking with the CNGS neutrino beam, and acting presently as the deputy Technical Coordinator for ICARUS-T600 at FNAL.
In parallel she has actively participated in intense R&D activities with several small scale LAr-TPC's at INFN-LNL (Italy), at CERN and at FNAL.

The Liquid Argon R&D facilities at Fermilab are an ideal location for this project, with a considerable infrastructure available: cryostats, cryogenic equipment, generic laboratory and electronics instrumentation, data acquisition and control systems.

In order to succeed in this research plan, the PI proposes support for 2 postdocs and Fermilab mechanical engineers and technicians.
Cost for materials and instrumentation will be minimized using existing Fermilab resources, specifically vacuum equipment, purity monitors to be used as drift chamber, HV power supplies, oscilloscopes, readout electronics, miniature cameras with vacuum tight enclosures for operations in cold, etc.
Miniature electrode structures will be produced in collaboration with highly specialized nanofabrication centers, such as the BNL CNF, following a model already in use for other Projects at FNAL. For this travel support will be needed.

Bibliography.

[1] L. Bagby et al., arXiv: 1805.03931 [physics.ins-det] (2018)
[2] MicroBooNE Collaboration, JINST 12, P08003 (2017)
[3] ArgoNeuT CollaborationPhys. Rev. D 99, 012002 (2019)
[4] M. Titov, arXiv:1308.3047 [physics.ins-det] (2013)
[5] A. Bondar et al. NIM A 556, 273 (2006)
[6] S. Murphy, oral presentation at ICHEP 2016
[7] G. Bressi et al, NIM A310, 613 (1991)
[8] J.G. Kim et al., arXiv: 0204033 [hep-ex] (2002)
[9] I. Jaegle et al. , arXiv: 1901.06657 [physics.ins-det] (2019)
[10] T. Oger et al., arXiv:1109.3856 [physics.ins-det] (2011)
[11] G. Caliandro et al., arXiv:1312.4503 [astro-ph.IM] (2013)

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