Electron multiplication in liquid argon TPC detectors for low energy rare event physics

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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 largely 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 ionization electrons, produced by the interaction of charged particles with the target medium and drifted by a uniform electric field over up to several 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 keV) [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. Quenching dopants can't be used to overcome this problem because, due to the gas-liquid temperature difference, 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].

Based on these premises, an R&D effort, funded by an LDRD grant, was initiated at Fermilab in 2018 to pursue the alternative strategy of controlled and stable electron proportional multiplication of drift electrons directly in liquid argon. The adopted approach takes inspiration from promising yet scarce literature [7][8], and consists in sub-micrometric anodic electrodes, 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.

The current effort has been focused on developing a greater understanding of charge amplification in liquid argon in terms of theoretical feasibility and practical manifestation, including the study of challenges due to stability, sparking and heat-induced bubble formation. The hardware component of this effort has focused on exploring different anode geometries in a controlled test-stand to quantify gain at different strengths of the electric field. This has been accompanied by the development of a comprehensive simulation toolkit capable of studying the potential for amplification in a variety of anode geometries through the precise mapping of local electric fields and a detailed simulation of the microphysics of electron transport and interactions at different field strengths. Preliminary simulation results from this effort suggest that localized electric fields of O(10^6 V/cm) can lead to amplification factors of O(10-100) in liquid argon which can be achieved in bulk electric fields of O(10^4 V/cm). These simulation results are strengthened by qualitative agreement observed between gas-phase simulation results compared to test-bench data. On the experimental side, while progress has been made in studying amplification performance in the liquid phase, results are still preliminary and necessitate further investigation. The improved understanding of the impact of anodic geometries on amplification gains are helping guide the design of ongoing experimental trials.

A relevant side benefit of the ongoing R&D effort worth mentioning is that the reduction of the electrode dimension allows for higher granularity and thus improvements in spatial resolution. Future detector design will benefit from a high flexibility in tuning the compromise between granularity and number of channels to be read out, depending on the specific experimental application.

The broader aim of developing lower-threshold detectors for noble elements via localized ionization amplification will require innovative developments on multiple fronts. Prototyping and feasibility studies will necessitate robust demonstrations through calibrations via radiological or neutron sources. Transitioning from proof-of-principle demonstrations with simplified anode geometries to scalable readout sensors, and appropriate readout electronics, will necessitate a parallel R&D thrust. Finally, the exploration of the broader potential of such detector concepts in terms of physics reach can help enhance motivation for such an effort. This motivates broader collaboration between groups with diverse skills and expertise, something we are hoping to foster and promote through this letter.

Eventually, new generation of single phase LAr-TPC detectors capable of exploiting the advances being pursued by the R&D promoted in this effort could revolutionize the experimental searches for low energy (< 100 keV) rare (~ 10^{-40} cm^2) events, allowing to measure interactions that previously would go undetected in such detectors, and providing access to information on article interactions such as the directionality of nuclear and electron recoils. This potential is well tied to a broad community push to explore new physics opportunities at low energies and as such is being suggested for community consideration in the upcoming snowmass process.

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