Snowmass2021 - Letter of Interest

Improving Large LArTPC Performance Through the Use of Photo-Ionizing Dopants

Topical Group(s):

(NF10) Neutrino detectors

(IF08) Noble Elements

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Abstract: (maximum 200 words)

A major challenge in large LArTPCs is the accurate measurement of the isotropic scintillation light signals. This is especially important when pursuing physics at the MeV scale where the anti-correlation between the energy deposited in scintillation and ionization leads to an energy smearing without the accurate utilization of both signals. In the context of large LArTPCs, accurate measurements of the scintillation light would require large amounts of photo-cathode coverage. To overcome this we propose the use of photo-ionizing dopants which aim to convert the isotropic scintillation light into directional ionization charge. This would have three benefits to LArTPC performance, an overall enhancement in the ionization signal, a breaking of the anti-correlation between light and charge, and a more linear detector response when large amounts of energy are deposited in small distances. For these to be integrated into future LArTPCs a program of R&D will be required to demonstrate the efficacy of these dopants and to build the analysis techniques that will enable their usage.

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The upcoming experimental program will provide us a rich future for the exploration of a large number of phenomena. One area of intense interest recently has been the expansion of the LArTPC-based physics program towards lower energies, generally focused near the MeV scale. This reach could be further expanded by using a pixelated readout, which can provide lower thresholds, less noise, and a smaller data footprint [1-4]. One complication associated with any exploration at the MeV scale in a massive LArTPC is the energy resolution that is achievable. **This LOI will discuss the prospect of using photo-ionizing dopants to enhance the MeV-scale performance of future massive LArTPCs.**

When energy is deposited into the detector medium of a LArTPC, it is spread between ionization and scintillation channels. The fractional contribution of each depends on the energy deposited and the electric field that is applied. When we are studying MeV-scale energy deposits this anti-correlation can directly impact the resolution of measured deposited energy. **Recently, both the LArIAT [5] and EXO-200 [6] collaborations have demonstrated that by utilizing this anti-correlation they are able to improve their measured energy resolution at the MeV scale.** For example, a hypothetical pixelated DUNE module with a percent-level energy resolution near the MeV scale could enable new physics goals for the DUNE program [7-12]. However, on account of the charge/light anti-correlations, achieving this level of precision with existing detectors requires a simultaneous measurement of the ionization charge and the number of scintillation photons produced, which is difficult to achieve in a large LArTPC even with a high level of photocathode coverage. The conversion of the isotropic scintillation light into directional ionization charge by doping the LAr photo-ionizing dopants at the ppm level could effectively break this anti-correlation and enable a high-precision measurement of the deposited energy.

Photo-ionizing dopants are a class of chemicals that have an ionization potential energy at or lower than the energy of a scintillation photon: ~9 eV for LAr and ~7 eV for xenon-doped LAr. These chemicals enter into solution with LAr, based on their vapor pressure, and when a scintillation photon impinges the molecule they eject an ionization electron. The use of these dopants was explored in the 1980s where their application was for use in collider experiment LAr calorimeters. In addition, the ICARUS collaboration published an analysis of a run where they doped a prototype detector with a photo-ionizing dopant (tetra-methyl-germanium, TMG) [13]. In each case, **these experiments observed a clear enhancement of the ionization charge liberated, especially pronounced in regions of high energy deposition which generally create additional scintillation light.** While enhancing the ionization charge is an attractive possibility in the context of calorimetric measurements one needs to clearly define the impact on the analysis of LArTPC data, especially with the cost of suppressing the scintillation light yield.

While the enhanced ionization yield would enable a more accurate method for sampling a larger fraction of the energy deposited in a LArTPC, there are practical implications that need to be addressed. One aspect explored by the ICARUS collaboration in Ref. [13] was the more linear detector response at high dE/dx. A common technique for establishing the identity of a particle in

LArTPCs is to study the energy deposited by the particle along its length. To accurately assess this one must convert the measured ionization charge back to the energy deposited through what is known as a “recombination correction” [14]. In a standard LArTPC, this is highly non-linear at large amounts of deposited energy but **the introduction of photo-ionizing dopants creates a significantly more linear correction from reconstructed charge to the deposited energy [13], this could aid in a more efficient particle-identification performance.**

One clear challenge with the introduction of photo-ionizing dopants is the suppression of the prompt scintillation signal that is often used to trigger the TPC readout and the location of the charge in the drift direction. While the efficient timing and triggering of LArTPCs are essential for surface detectors,the needs for high precision neutrino-timing and triggering are highly reduced for detectors located deep underground . In the absence of scintillation light, the timing of the interaction can be assessed directly from the diffusion of the ionization charge recorded. **During the transit of the ionization signals towards the wires, they will diffuse (or broaden), and this feature enables the measurement of the particle timing and position in the drift direction [15].** While this provides less-precise timing information than the scintillation light (μs vs. ns) this should be sufficient for associating the neutrino interaction to a 10 μs long beam spill. **To perform this diffusion-based time tagging it is required that the ionization readout retain sufficient time-domain information to enable this measurement.**

The prospects of utilizing photo-ionizing dopants to enhance the global performance of LArTPCs is potentially beneficial to enhance physics programs, but to fully realize this potential we are required to verify their efficacy through a rigorous R&D program. We have identified two key areas that will need further studies: chemistry and detector. While a number of dopants have been studied in the past [16,17] the list of candidate chemicals should be revisited through the lens of modern synthesis tools. This would enable us to maximize the quantum efficiencies of these chemicals. Further, we will need to study the long term stability of any substance that we add to the LAr. This includes whether the dopants degrade as charged particles pass through the materials. This can be tested directly in a test-beam program, similar to the LArIAT program, where the ionization and scintillation signal strengths can be tracked. In addition, we would want to study the reactivity of these chemicals with the materials that make up the detectors and the cryogenic systems. These tests would be critical when designing the LAr purification system to verify that one would not filter out the dopants. Beyond these tests, one would also need to verify the performance of the detector in the presence of these dopants including tests of the stability of the high voltage systems, measurements of ionization electron drift velocity in the presence of dopants, and any impact dopants would have on the diffusion of the drifting ionization electrons.

The LArTPC-based program provides our community with rich prospects to probe physics scales we have not actively pursued in the past. As we begin to prioritize physics topics that we will be pursuing in the decades to come, it is critical that we design detectors that allow us to explore as broad a physics program as possible. We propose that R&D associated with utilizing photo-ionizing dopants in large LArTPCs can greatly expand the precision by which we can explore the MeV-scale.

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