Scintillating and Quenched Gas Mixtures for HPGTPCs

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1 Motivation for Scintillating TPCs

High pressure (10-15 bar) gaseous time projection chambers (TPCs) are a technology of increasing relevance to the field of neutrino physics and rare event searches. Two contemporary examples are the gaseous "ND-GAr" detector [1] that forms part of the near detector complex of the Deep Underground Neutrino Experiment (DUNE) [2], with the goal of constraining systematic uncertainties and flux monitoring at short baselines in the neutrino beam; and the NEXT program [3], with the goal of mounting an ultra-sensitive search for neutrinoless double beta decay using high pressure ^{136}Xe. In addition to neutrino physics applications, there are many other possible applications of high pressure gas detectors, including in the fields of dark matter searches [4], cellular imaging [5], collider physics, and beyond [6].

While there is a rich history of R&D in gaseous electronics [7, 8], much remains to be understood and optimized at high pressures and large scales sought by experiments in both the near- and mid-term. An area of much recent activity, largely spearheaded by dual-phase chambers, is the deeper study of scintillation in gases [9–14]. New scintillation mechanisms such as molecular electroluminescence or neutral bremsstrahlung have been uncovered and technologically exploited [15–17]. Despite recent progress, the realization of a stable, VUV-quenched gain, scintillation-capable, 10-15 bar TPC remains elusive. This LOI discusses pathways toward this this goal.

TPCs using argon-based gas mixtures typically employ avalanche gain to amplify signals from drifting charge. In this process, electrons entering a region of large electric field are multiplied through ionizing collisions to enhance the detectable signal above electronic noise on the readout channel [18]. To obtain stable gain rather than a runaway avalanche (or spark), a quench gas is added, often CH_4 or CO_2. The role of the quench gas is to absorb or inhibit VUV photons that would have otherwise liberated additional electrons from the metal electrodes, initiating streamers. An unfortunate consequence is that the copious VUV-scintillation that would usually accompany the primary interaction is eliminated. There is no presently demonstrated solution which simultaneously achieves quenched gain and also allows readout of primary scintillation at usable levels.

There are several reasons why such a capability is desirable. Considering surface-level TPCs in neutrino beams such as DUNE ND-GAr, experience with MicroBooNE [19] has shown scintillation light to be a critical tool for distinguishing neutrino interactions from cosmogenic backgrounds. While some background rejection can be achieved by direct tagging of muons using external scintillator [20], such approaches are not comprehensive enough to provide background rejection for all topologies of interest. Muon-less events, for example, from neutral currents, and backgrounds from cosmogenic neutrons, cannot be constrained using external taggers. Given that the near detector must provide a constraint on the flux to provide normalization for an oscillation measurement, selection biases introduced by cosmic ray contamination that will be absent at the much deeper far detector are of critical concern. For optimal physics reach in all channels, a neutrino near detector is thus likely to be much enhanced by gas scintillation readout.

A second example is provided by rare-event detection experiments, where there is no time-stamped beam to establish interaction time. In such experiments, in order to apply a correction for the finite electron lifetime that attenuates charge during drift, the original position of the event must be known. This is measured via the time between the event and arrival of charge at the readout plane, the former being accessed via the prompt flash of scintillation light. Generally speaking, without prompt scintillation readout, no drift correction is possible, inhibiting energy resolution. Fiducialization of cathode-originating beta decays and other backgrounds also relies critically on establishing event timing, and without primary scintillation these important classes of background may become irreducible.

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2 Approaches

The suppression of UV-induced streamers during the avalanche gain process and simultaneous collection of primary UV light appear to be diametrically opposing requirements. However, it remains far from clear that they are mutually exclusive. Two main approaches can be pursued for optimizing a gas mixture for VUV-quenched gain and scintillation detection, which are distinguished by their emission wavelength range.

a) Infra-red readout: Recent attention has been given to the commonly overlooked infra-red component of noble element scintillation, expected to be emitted and possibly enhanced, even in a fully quenched gas mixture. The challenge associated with this approach is that the known strong molecular infrared emission features are at wavelengths longer than the efficiency window of common infrared SiPMs, and so the scheme must be based on atomic infrared emission; this component may be rather weak in high pressure gas mixtures, but whether its weakness is prohibitive is a question that must be confronted with data.

b) Near-UV or visible readout: There are plausible methods to balance the needs of quenching with those of light collection. Pure argon gas emits at 128 nm, which is energetically far above the work function of most metals, so that the photoelectron yield in unquenched argon is high [21]. However, it is well known that addition of dopants can shift this to longer wavelengths, where significantly reduced secondary photoelectron yields are expected. Addition of sub-percent quantities xenon, for example, efficiently shifts the light to 175 nm [22], which is still above most work-functions, but expected to reduce photoelectron yield by an order of magnitude [21]. Use of higher pressure gases increases back-scattering of electrons into materials [23–25] thus further reducing the effective yield, suggesting that the limitations on gain in high pressure systems will be relaxed relative to lower pressure systems at similar reduced fields.

Addition of further dopants can shift scintillation to longer wavelengths. Candidates include nitrogen, reported to result in shifting of light to 337 nm [26, 27] in the gas phase. At this wavelength, the photons would be below the work function of most electrode materials, and so fully quenched gain should be possible. However, the visible photon yield in high pressure Ar-N_2 mixtures has not been characterized, to our knowledge, and must be studied experimentally. A second promising dopant is CF_4, which has direct visible scintillation and has shown hints of wavelength-shifting in argon too, and can also be used as a quench gas in argon. Related gases of the CFC family, such as C_2F_6 are also viable candidates. Yet another approach would be use of the argon third continuum (175-300nm) within ternary mixtures to provide suitable wavelength cutoffs.

3 Outlook and Plans

An ongoing program of R&D at the University of Texas at Arlington in collaboration with Santiago and Coimbra Universities in Europe aims to systematically map the space of scintillating gas mixtures of argon with admixtures of xenon, nitrogen, hydrocarbons and and fluorinated compounds. In addition to measuring scintillation and electroluminescence, detector operating parameters including high-voltage strength, electron mobility, transverse and longitudinal diffusion are being systematically explored. The stability of gain is monitored with small-scale replicas of the intended ND-GAr readout (based on multiwire proportional chambers, or MWPCs). Fundamental work on micro-physical modelling and computation is being advanced within the framework of the recently refactored PyBoltz code [28], including direct incorporation of the complex energy cascade processes involved in multi-species scintillation [29] in parallel with electron transport simulation. Such a code-base, suitably and widely validated, promises a major intellectual advance in unification of the microscopic descriptions of electron propagation and light production within gas mixtures of interest to gaseous technology. Novel electroluminescent gain structures are being explored to employ partially stabilized gas mixtures, with promising early performance already demonstrated [30].

If a suitable marriage of gain geometry, gas stabilization and light collection can be achieved, this would represent a ground-breaking advance for particle detection with high pressure gases. On the other hand, it is clear from examination of previous efforts in this field that the landscape is wide and uneven; accumulation of disorganized subsets of data in specific mixtures under specific conditions no longer appears key to unlocking new capabilities. In order to provide compelling new pathways for exploration and to fully understand the systems already considered, not only are more complete and systematic studies required, but also a deeper understanding of the fundamental scintillation process and its relationship to other detector parameters in multi-partite gas mixtures.

Such a “gas mixture genome” project will require steady investment over a sustained period. If successful it will yield comprehensive datasets and a new generation of theoretical tools and software packages that can be used to unlock new capabilities for particle detectors across all sub-fields where noble gas detectors are a workhorse. The fundamental advances in this area will also doubtless greatly influence the more complex project of optimizing and understanding mixtures for liquid or two-phase noble detectors. We advocate here that fundamental studies of scintillating gas mixtures is an area that should be given increasing attention in the US / World program, during the 2021 Snowmass period.

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