Snowmass2021 - Letter of Interest

Multi-modal Pixels for Noble Element Time Projection Chambers

NF Topical Groups: (check all that apply □/■)

□ (NF1) Neutrino oscillations
□ (NF2) Sterile neutrinos
□ (NF3) Beyond the Standard Model
□ (NF4) Neutrinos from natural sources
□ (NF5) Neutrino properties
□ (NF6) Neutrino cross sections
□ (NF7) Applications
□ (TF11) Theory of neutrino physics
□ (NF9) Artificial neutrino sources
■ (NF10) Neutrino detectors
■ (IF02) Photon Detectors
■ (IF08) Noble Elements

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Abstract:
In this LOI, we propose the development of multi-modal pixels for the simultaneous detection of VUV scintillation light and femtoCoulomb ionization charge. This novel readout concept would boost the physics sensitivity of future massive noble element Time Projection Chambers (TPCs) for physics at the low energy (neutrinoless double beta decay, rare event searches, atmospheric neutrinos, supernovae), as well as to heavy sterile neutrinos and dark matter searches.

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Noble element Time Projection Chambers (TPCs) are the detector technology of choice for the next generation of discovery at the intensity frontier. TPC applications range from dark matter (e.g. ArDM, DarkSide, XENON-NT and LZ [1,2,3,4]), rare decays and capture (e.g. MuCap [5]), neutrino oscillations and nucleon decay (ICARUS, SBN, DUNE [6,7]), to neutrino less double beta decay (NEXT, EXO [8, 9]). Building from the considerable legacy experience in this technology, the TPCs detection enhancements will unlock discovery level measurements in a number of fields.

The detection strength of TPCs hinges on the multiple channel response generated by the passage of charged particles in noble elements: heat, ionization charge and scintillation light. Depending on the physics of interest, however, noble element detectors have historically exploited fully only one of the three signal components: generally charge collection for neutrino detectors and light collection for dark matter. Recent work has shown how leveraging the combination of light and charge boosts the reconstructed energy resolution and can allow for lower energy thresholds [10, 11]. The combined measurement of the scintillation light and the ionization charge gives the TPC the capability of being a fully active 5D detector with 3D tracking, calorimetric reconstruction, and timing resolution. Recent simulation studies have shown how pixelated TPCs [12,13] for ionization charge detection are potentially superior in resilience and physics performance compared to the traditional wire design [14]. On the light side, the last 20 years in dark matter direct detection and neutrinoless double beta decay with Xe detectors have showcased the importance of a powerful light collection system.

While the benefits of pixelated TPCs and powerful light collection systems are clear, combining the two in a single system is challenging. In traditional wire readouts, the empty space between consecutive wires allows the VUV light to reach the light collection system mounted behind the anode plane. This solution cannot be applied in pixelated TPCs, where pixels are embedded in PCB opaque boards which absorb the VUV light. Even if a different placement could be possible for some traditional light collection systems, the photocathode coverage is likely to be poor, non-uniform and the actual viability of such a solution still needs to be demonstrated, especially for kTon applications [15].

We propose the development of a multi-modal pixel technology which can read out simultaneously femtoCoulomb ionization charge and VUV light. We envision a first implementation of this technology by coating pixel-based charge readouts with a thin semiconductive film sensitive to VUV photons. When struck with a VUV photon, the semiconductive coating would release an electron-hole pair, and move the electron in the electric field toward a pixel button. If the field near the button is sufficiently high, this would lead to an avalanche charge collected by the button. With the proper choice of photoconductive material such a device could have a broad frequency response and thus detect the full spectrum of light produced in Noble Element TPCs.

This technology would solve the challenge of collecting light for pixelated readouts in the most elegant way: by providing a potentially high efficiency light collection system with massive photocathode coverage, fine granularity, and zero additional readout channels. By coating all the anode pixels, the photocathode coverage and granularity would coincide with the TPC anodic plane coverage by construction. Such a system would boost the coverage of kTon scale TPCs by three orders of magnitude with respect to current designs [16,17]. The direct detection of VUV light would make the use of wavelength shifting materials obsolete. The high granularity of such a detector would open a new window to imaging with scintillation light and pave the road for light augmented calorimetry at the kTon scale.

The realization of a full multi-dimensional readout over the full spectrum of produced signals of noble element TPC's remains a key instrumentation challenge. The exploration of coating a dielectric surface with a VUV sensitive surface requires a cross-cutting collaboration with solid state, condensed matter, and material science physics.

The R&D for suitable photoconductive coatings and multiple modality pixels have been funded via a Fermilab LDRD grant and Dr Asaadi's Early Career Award in 2020. The starting choice for the coating is amorphous selenium (a-Se), which is already used in imaging for medical applications [18]. The literature on a-Se [19,20] reports a particularly favorable attenuation coefficient for photons at 128 nm (LAr scintillation light wavelength), which results in a conversion efficiency for single photon to electron-hole pair greater than 99% for thin coatings ($> 1\ \mu$m). If avalanche gain in the semiconductor is achieved, such a technology has the potential for extremely high single photon quantum efficiencies ($> 90\%$). A full simulation of the electrical and optical properties of selenium based on density functional theory (DFT) [21] and post-DFT is underway; preliminary results based on DFT and ab initio molecular dynamics of a-Se model show qualitative agreement in the VUV with historical experimental data.

Another promising avenue for multiple modality detectors is the development of pyroelectric light sensitive pixels, especially based on ZnO. Modern "pyro-phototronic" devices combine light induced pyroelectric effect along with various semi-conductor effects to respond to a broad light spectrum with low dark currents and a fairly quick response time ($< 1\mu$s). A recent application of these devices has demonstrated they can be used at cryogenic temperatures (77 K) and UV (325 nm) illumination [22], and they can be integrated in CMOS [23].

If multi-modal pixels can be made operational in gas, cryogenic liquid, and low radioactive background environments then they could become a ubiquitous use technology. However, if even one of these applications can be realized such an ambitious undertaking has the potential for truly transformative progress in the field of noble element detectors: a powerful light detection system combined with a pixelated TPC would allow novel concepts for fast triggering, and a reduction of the energy detection threshold. This would boost the physics sensitivity of future massive underground detectors for physics at the low energy (neutrinoless double beta decay, rare event searches, atmospheric neutrinos, supernovae), as well as of the DUNE near detector to heavy sterile neutrinos and dark matter searches.

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