Recoil Directional Sensitivity and Micron-Precision Spatial Reconstruction

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Executive Summary

Large-scale inert element Time Projection Chambers (TPCs) offer unique capabilities for rare process searches. Advances in this technology's ability to image low-energy signatures can further expand their applicability and impact in high energy and nuclear physics experiments. In particular, enabling micron-level imaging through a number of different technological advances can expand the physics reach of such detectors including the measurement and tracking of nuclear recoils from Coherent Elastic Neutrino-Nucleus Scattering (CEvNS), measurement of supernova neutrinos, neutrinoless double-beta decay searches, and broader rare-event searches with low-energy signatures, including the search for particle dark matter.

[1] Directionality in dual-phase TPCs: Currently proposed direct detection experiments aspire to probe dark matter interactions down to the "neutrino floor" (or into the "neutrino fog" (1)) over a wide range of energies. The onset of the fog is widely construed as the end of the line for nuclear recoil direct detection experiments using existing methods. However, a detector sensitive to a directional anisotropy of the direct detection rate would have powerful discrimination against most or all neutrino backgrounds. Direction-sensitive nuclear recoil detection is being pursued by a number of collaborations world-wide (reviewed in (3, 4)), many of them based on negative ion drift in low pressure gases (6). It is however difficult to conceive a gas target experiment that could reach an exposure competitive with the currently proposed ton-years of liquid noble gas or other condensed phase detectors.

Direction-sensitivity of the specific ionization for tracks in a LAr-TPC has been observed for MeV proton recoils (7), arising from the different amounts of columnar recombination occurring when a track is drifted at varying angles with respect to its long axis. A directional response effect was also sought in the dark matter recoil energy range by a subgroup of the DarkSide collaboration (8), but could not be unambiguously established with the available statistics. More recently, the ReD collaboration (9) is searching for direction-sensitive discriminants in the WIMP- recoil energy range. Continued experiments with ReD will fully explore the recoil energy and drift field space, and careful analysis will search for direction-sensitive signatures.

Theoretical studies modeling the electron drift mobility in LAr near its normal boiling point give good agreement with experiment (10). However, in Ref. (13) a substantial electron drift was

measured in LAr, operating at a reduced liquid density achieved by elevated temperature and pressure (T ≥ 120 K, P ≥ 26 bar).
These results were in qualitative agreement with a model calculation. This implies that the mean free path of electrons in LAr at these conditions is large enough so that one can reasonably expect detectable signal differences depending upon the relative directions of track, drift electric field, and magnetic field. Small scale LAr-TPC studies of short tracks under similar conditions should be undertaken to search for useful directional sensitivity. Eventual tonne-scale experiments exploiting any discovered signature would be technically demanding but remain well within the present-day commercial and scientific state of art.

[2] Directionality in gaseous TPCs (15): Another technological development aiming to expand detection capabilities of noble element detectors aims to enable O(10-100) μm resolution in high-pressure gaseous argon TPCs through the use of high-granularity Gaseous Electron Multiplier (GEM) readout. This effort aims to first perform feasibility studies of tracking resolution for existing GEM technologies in different gaseous argon environments, iterating on readout, GEM, and detector design including gas-mixtures to achieve the charge thresholds and position resolution needed to observe CEvNS interactions at meaningful rates from existing and future sources of sub-100 MeV neutrinos.

[3] Micron-precision particle tracking (16): One approach being pursued to enable micron-scale tracking is a dual-readout TPCs: a high pressure gaseous TPC collecting charge from both the negatively charged carrier (electrons or ions) at the anode and the positive ions at the cathode. The use of positive ions (which remain thermal during their drift) greatly reduces diffusion, which drives the spatial limitation of the current TPC technology. In a dual-readout TPC, a pixelated anode plane would allow a “coarse” (mm to cm) event reconstruction to be mapped onto a small cathode region of interest where the local tracking in the tens of micron region is performed. For readout of the positive ion signal, there are at least two distinct but promising technological solutions: TopMetal and Ion Microscopy. The recently developed Topmetal-II -- a CMOS pixel sensitive to direct charge -- has demonstrated functionality when embedded in a standard 0.35 μm CMOS Integrated Circuit process (17). Techniques for ion sensing and microscopy in gas are under development for neutrinoless double beta decay (0νββ) searches (barium tagging). A system with a fluorescent ion-sensing layer probed by a mobile laser excitation source and EMCCD camera could resolve projected ion tracks with micron precision, seconds to minutes after the original interaction. Positioning of the camera with 2 nm spatial resolution has been demonstrated for single ion detection in (18).

Instrumentation requirements to achieve physics goals (list)

- [1,2,3] O(10-100) μm position resolution and O(10-100) keV energy thresholds to improve neutrino physics reach
- [2,3] Avalanche multiplication in either GAr or pixel-based detector for 10 um resolution in a gaseous TPC
- [1,2,3] Directional sensitivity for ~keV scale nuclear recoils for dark matter detection

Significant instrumentation challenges (list)

- [1,2,3] Limiting gaseous argon diffusion for improved resolution.
- [2,3] Development of electronics for pixel-based GAr GEMs and LAr multi-modal pixels.
- [1] Dual-Phase LAr-TPC capable of operation up to ~ 40 bar and ~ 140 Kelvin and a magnet capable of ~ 5 T surrounding TPC. Precise temperature/pressure control will be necessary. Other TPC instrumentation challenges such as high pressure HV feedthroughs and electroluminescence signal (ionization readout) production under the stated conditions must be met.
- [3] Positive ion sensing technology: top-metal or ion microscopy

Relevant physics areas (e.g., low-mass DM, solar neutrino oscillations, CEvNS)

- Neutrino physics: CEvNS, supernova, atmospheric neutrino, neutrinoless double-beta decay interactions. Measurements of cross-sections and neutrino oscillations, as well as enhanced rare-interactions searches.
- Direct dark matter detection

Relevant cross-connections (e.g., other topical groups, other white papers)

Further reading (e.g., reference for existing TDR, reference paper, etc.)

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