

## Noble liquid working group

### DRAFT:

Detectors using noble elements as the detection medium, such as liquid and gaseous argon and xenon, have become a prime technology for science drivers such as neutrino physics, including precision studies of neutrino oscillations and astrophysical neutrinos, searches for neutrinoless double beta decay and the measurement of coherent neutrino-nucleus scattering, and for direct dark matter searches. These experiments can be very large, ranging up to kiloton scales, and many plan to run for an extended time, even decades. It is therefore essential to ensure that their physics reach is optimized. Three main PRDs are identified.

**PRD \#1: Develop large area, high granularity, high efficiency signal collection technologies.** The signal detection from noble element detectors includes detecting charge from ionization, detection of vacuum ultra-violet (VUV) photons from scintillation, and novel channels such as bubble formation or quasiparticles. Unambiguous 3D imaging utilizing these signals necessitates R&D into novel pixel charge readout, light detection techniques directly sensitive to VUV signals, and the ability to shift VUV wavelengths to visible wavelengths, among others, to realize large area, highly efficient detectors capable of providing the imaging detail, timing, and calorimetric information and dynamic range needed by noble element detectors. The **three key challenges are:**

- 1) Addressing requirements for large channel count, low power consumption, resilience to single point failure, and low energy threshold requirements to enable next generation physics reach with large scale noble element detectors;
- 2) Improving detection of all wavelengths of light, requiring innovation with existing silicon-based detectors, exploration of non-silicon-based technologies sensitive to VUV signals, research into infrared and Cherenkov light sensors, and further development of wavelength shifting technologies and techniques;
- 3) Exploring further signal amplification for both light, charge, and heat collection to allow for lower detection thresholds, which could significantly increase the physics reach of these detectors.

**PRD\#2: Develop calibration techniques to understand the response of noble elements to very low energy nuclear recoils, to better resolve energy depositions from different particles of all energies, and to fully characterize the entire volume of very large scale liquid and gaseous detectors.** Effective calibration is a critical component for any science driver, as the ability to resolve a new physics signal, reject backgrounds, tease out small shape effects, or precisely measure detector parameters requires deep understanding of detectors only possible through calibration. Future generations of noble element detectors present the following calibration **key challenges:**

- 1) Understanding the response of noble elements to sub-keV recoils, an essential element for dark matter experiments;
- 2) Uniform calibration of ton- and kiloton-scale detectors throughout their volume in the relevant energy range;
- 3) Detailed understanding of the electric field response;
- 4) Improving energy resolution, particle and event ID, and topology to resolve signals and reject backgrounds. This includes responses to particles over a wide range of energies.

**PRD#3: Develop strategies to address known and hidden challenges associated with scalability of future noble element experiments.** Neutrino and rare-event search experiments continue to grow, both in physical size and in sensitivity, and with this growth comes a number of challenges. As the required sensitivity of rare-event experiments, such as the search for particle dark matter and neutrinoless double-beta decay, increases, so does the need for radiologically pure materials and their high throughput screening, as well as removal of radioactive impurities. Delivering such high-purity noble-liquid targets will require advances in cryogenics and purification systems. Larger detector volumes imply longer drift distances for TPCs, which require higher drift voltages and purity than are achieved in the current generation of experiments. Delivery of high voltage without electrical breakdown requires advances in the design of high voltage feedthroughs and will require development of facilities to test future high voltage solutions. In addition, the timely procurement and clean storage of large quantities of noble elements is an emerging need of future experiments, as is the ability to perform isotopic separation for enriched sources (e.g. for neutrinoless double-beta decay) and background suppression (e.g. underground argon for dark matter searches). The possibility of magnetizing future large-volume noble element detectors also presents scalability challenges, and will likely require further development of high-temperature superconductors. Finally, larger noble liquid detectors will produce a deluge of data that will overwhelm existing computing resources without new R&D to approach all areas of computing from data acquisition to data analysis. Developing strategies and technologies to deal with known scalability challenges while remaining flexible to overcome new challenges as they arise will enable successful future generations of experiments.

**Key challenges:**

- 1) Developing very high voltage delivery solutions, including the use of resistive materials, and understanding the dielectric properties of the different elements under different purity conditions;
- 2) Developing large-scale purification solutions to study the effects of and removal of impurities, including both electronegative species and radioactive contaminants;
- 3) Developing new solutions for screening and procurement of low-background detector materials, including electronics components such as cables, and understanding how those backgrounds generate signals in sensitive detectors;
- 4) Developing isotope separation and enrichment solutions;
- 5) Understanding how to trigger, handle, process, and analyze the exponential increase in data volumes that will come with future large scale noble liquid detectors.

It is important to ensure that techniques that utilize noble elements in novel ways should be encouraged. Noble elements have many useful properties for particle detection, and we cannot predict what a new technique might be able to accomplish.

Finally, there are clear infrastructure needs that will be important for R&D over the long term. Below we present a list of facilities and highly qualified personnel that will play a crucial role for future experiments.

- **ASIC designers:** There is expertise in ASIC design at the different national labs, but in order to match the future demands for large-scale detectors, it is essential that the expertise remains accessible and that there are enough resources.
- **Procurement and clean storage of large quantities of noble elements:** As the detector increase in size, procurement of large quantities of noble liquid or gas will become a concern. Similarly, large-scale storage solutions and facilities will be needed. As there are no concrete solutions at the moment, special attention will be needed for the future.
- **Purification of large quantities of noble gases/liquids:** The large-scale detectors will require large quantities of noble liquid/gas with high purity, that cannot be met by industry. Purification facilities may be crucial for the future generation of detectors.
- **Isotopic separation:** Some rare event search experiments will need a medium depleted of radioactive isotopes (e.g. underground argon for dark matter searches and depleted xenon for dark matter) and some will need medium enriched with the appropriate isotope (e.g. Enriched  $^{136}\text{Xe}$  for neutrinoless double-beta decay). Access to facilities (such as the DOE isotope enrichment program) that can perform such isotope separation will be essential.
- **Clean photodetector fabrication facilities:** Several noble element detectors will be used for rare events searches and having access to clean fabrication facilities will be very important.
- **Radiopurity screening and procurement of large quantity of radiopure material:** In order to construct detectors with very high radiopurity, experiments will need access to radiopurity screening facilities, which are typically located underground. As the demand increases for different large-scale experiments, these facilities will be in high demand. In addition, the demand for radiopure materials (e.g. electroformed Cu, clean PCB material or radiopure cables and connectors) will significantly increase, and there will be a need for dedicated facilities.
- **Test beam facilities:** Testing beam facilities, such as the FNAL and CERN ones, are of high interest for calibration of LAr detectors for neutrino physics in the relevant energy ranges. In addition, the availability of low-energy neutron beams for at-threshold calibrations will be very important for rare event search experiments.

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Computational challenges, DAQ, Trigger, GPU optical simulations (in PRD#4?)  
Readout electronics for photon detectors

(JLR added this in PRD#3) Magnetization of LArTPCs (possibly for the 4th DUNE module),  
development related to high-temperature superconductors  
(Should we add this in PRD#1? Decision: no, because it doesn't really require new R&D) Active  
veto via photon detection system in non-active TPC volumes  
(JLR added into PRD#3) Calibration of LArTPC field response  
(Already covered) Improving signal collection efficiency  
(Already covered) High-throughput isotopic separation

Old 3 and 4:

~~**PRD#3: Develop large-capacity strategies to address the needs of future experiments with respect to radioactivity levels, chemical purity, fluid storage and handling, and isotopic segregation.**~~ As the required sensitivity of rare-event experiments, such as the search for particle dark matter and neutrinoless double-beta decay, increases, so does the need for radiologically pure materials and their high throughput screening. At the same time, the chemical purification of noble fluids needs to be carried out at rates that allow fast turnaround times for larger, future experiments with capabilities to remove efficiently any radon-related backgrounds. In addition, the timely procurement and clean storage of large quantities of noble elements is an emerging need of future experiments as is the ability to perform isotopic separation for enriched sources (e.g. for neutrinoless double-beta decay) and background suppression (e.g. underground argon for dark matter searches). Developing technologies and infrastructure in these areas are critical for the success of the next generation of noble element experiments. ~~The **key challenges are:**~~ 1) Developing large-scale purification solutions to remove impurities, including radon.  
2) Quantifying the impact of different contaminants on signal collection.  
3) Developing new solutions for low-background electronics components, such as cables, printed circuit boards, and for detector materials. Capabilities to assess the exact radioactive contamination should be developed; 4) Developing isotope separation and enrichment solutions.

**PRD#4: Develop strategies to address known and hidden challenges associated with scalability of future noble element experiments.** Neutrino and rare-event search experiments continue to grow, both in physical size and in sensitivity, and with this growth comes a number of challenges. Larger detector volumes imply longer drift distances for TPCs, which require higher drift voltages and purity than are achieved in the current generation of experiments. Delivery of high voltage without electrical breakdown requires advances in the design of high voltage feedthroughs and will require development of facilities to test future high-voltage solutions. Understanding the dielectric properties of noble elements will be highly beneficial for developing new systems. Delivery of increasingly high-purity noble-liquid targets also requires advances in cryogenics and purification systems. Evaporation of wavelength-shifting films and production of reflectors with appropriate radiopurity and performance requires development for increasingly large areas. Scaling will bring to light new challenges that have yet to be considered. Developing strategies and technologies to deal with known scalability challenges while remaining flexible to overcome new challenges as they arise will enable successful future generations of experiments. **Key challenges:** 1) Developing very high voltage delivery solutions, including the use of resistive materials, understanding the dielectric properties of the different elements under different purity conditions.  
2) Developing data