MAX - Multi-ton Argon & Xenon

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Project Summary

Evidence for the existence of dark matter is now compelling, but its nature remains a fundamental mystery. Particularly intriguing is the possibility that dark matter is made of Weakly Interacting Massive Particles (WIMPs). WIMPs may be detectable by their collisions with nuclei on Earth, but the low expected rate of such collisions and low energy of the recoil nuclei requires massive detectors with extremely low background rates, located in a deep underground laboratory. The development of a Deep Underground Science and Engineering Laboratory (DUSEL) will enable the deployment within the U.S. of WIMP detectors several orders of magnitude more sensitive than those operating today.

Liquid argon and xenon are promising media for WIMP detection due to their efficient conversion of energy from WIMP-induced nuclear recoils into both ionization and scintillation. In a Time Projection Chamber (TPC) scintillation and ionization can be independently detected and spatially resolved through large volumes of liquid. The relative size and time dependence of these signals permits discrimination of nuclear recoils from background events. By exploiting these methods and the self-shielding capability of the dense liquids, the leading xenon and argon TPC experiments have already achieved competitive sensitivity to WIMPs.

In 2007, the XENON-10 experiment reported a spin-independent (SI) cross section limit of $\sim 10^{-43}\,\mathrm{cm}^2$ and the WARP argon experiment reported a limit of $10^{-42}\,\mathrm{cm}^2$. Since mid-2008 the XENON collaboration has been operating at Laboratori Nazionali del Gran Sasso (LNGS) the first WIMP dark matter detector at the 100-kg scale (XENON-100). The Princeton group is participating in the WARP-140 kg experiment, now being commissioned at LNGS. Both experiments are expected to reach sensitivities of $\sim 10^{-45}\,\mathrm{cm}^2$ or to detect a handful of WIMPs if the cross section is $\sim 10^{-44}\,\mathrm{cm}^2$.

To make a convincing detection of dark matter, measurements of the interaction rate on multiple target nuclei will be required. Recognizing the significant synergy between argon and xenon as target/detectors for dark matter and the common engineering challenges of building liquid TPCs at the ton scale and beyond, we have decided to share knowledge and expertise and to design in parallel a large argon and a large xenon detector in a single collaboration: "Multi-ton Argon and Xenon TPCs" (MAX for short). Each detector will have sensitivity to the WIMP-nucleon cross section of $10^{-47}\,\mathrm{cm}^2$, 3–4 orders of magnitude better than existing limits. Both will be proposed for the DUSEL Initial Suite of Experiments (ISE). Together they will explore the most interesting region of the SUSY parameter space for WIMP dark matter, with the important features of verifying the A^2 dependence of the SI cross section and the spin dependent coupling offered by the xenon target.

The use of a common engineering team to develop the design of several major subsystems shared by the argon and xenon detectors will realize significant savings in time and cost while enabling an effective sharing of already-tested technologies.

Two important new technologies developed by collaboration members greatly enhance the power of the present collaboration to design the best xenon and argon detector system for the discovery and identification of WIMPs: (1) the development within the XENON collaboration of a new low-radioactivity, high-quantum-efficiency hybrid photomultiplier tube, the Quartz Photon Intensifying Detector or QUPID, designed at UCLA in partnership with Hamamatsu and (2) the discovery of underground sources of argon gas low in the isotope ^{39}Ar by the Princeton and Notre Dame groups, supported by the NSF. Designs incorporating these developments can achieve larger sensitive masses with much lower backgrounds than would otherwise have been possible.

INTELLECTUAL MERIT: The proposed activity will lay the engineering foundation for the next generation of larger noble liquid detectors, designed to advance our knowledge of elementary particles and cosmology in fundamental ways by detection of extremely weak, rare, low energy phenomena at DUSEL. These detectors will either detect WIMP dark matter for the first time or exclude a substantial fraction of the favored parameter space. The work will also prepare the way for a following generation of still-larger detectors (10 ton xenon TPC, 50 ton depleted argon TPC). These will be required to detect WIMP dark matter if the cross section is below the $10^{-47}\,\mathrm{cm}^2$, or to perform high-statistics, detailed studies of WIMP properties if WIMP dark matter is discovered using DUSEL-ISE experiments.

BROADER IMPACT: The proposed activity will advance the development of DUSEL and its scientific and educational mission in a variety of ways: (1) it will help the visibility of DUSEL as an international facility, through cooperation and partnership of US universities and national laboratories with European and Japanese groups; (2) it will offer an excellent opportunity for the training of students, who will have a chance to contribute to the success of a cutting edge project in fundamental science and advanced engineering; (3) it will benefit society through commercial applications of noble liquid detectors and associated technologies in areas ranging from national security to medical imaging; (4) it will support continued development of successful EPO programs such as the Princeton-Abruzzo-South Dakota summer school for high school students.

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II. INTRODUCTION

There is a wide range of astronomical evidence that the visible stars and gas in all galaxies, including our own, are immersed in a much larger cloud of non-luminous matter, typically an order of magnitude greater in total mass. The existence of this "dark matter" is consistent with evidence from large-scale galaxy surveys and microwave background measurements, indicating that the majority of matter in the universe is non-baryonic. The nature of this non-baryonic component is still totally unknown, and the resolution of the "dark matter puzzle" is of fundamental importance to cosmology, astrophysics, and elementary particle physics [1–3].

A leading explanation, motivated by supersymmetry theory, is the existence of as yet undiscovered Weakly Interacting Massive Particles (WIMPs), formed in the early universe and subsequently clustered in association with normal matter. WIMPs could, in principle, be detected in terrestrial experiments by their collisions with ordinary nuclei, giving observable low energy (<100 keV) nuclear recoils. The predicted low collision rates require ultra-low background detectors with large (0.1–10 ton) target masses, located in deep underground sites to eliminate neutron background from cosmic ray muons. The establishment of the Deep Underground Science and Engineering Laboratory for large-scale experiments of this type would strengthen the current leadership of US researchers in this and other particle astrophysics areas.

The discussion in Sec. III shows that a genuine coherent dark matter signal can be identified by two features (i) the cross section per target nucleus contains a term proportional to the square of the target atomic number A and (ii) its recoil energy spectrum gives an estimate of the WIMP mass which must be independent of the target material. Identification by these features requires two target elements significantly different in A, ideally in detectors of similar principles and configuration. This proposal takes advantage of the fact that such detectors have already been developed for Liquid Ar (LAr) and Liquid Xe (LXe), with A=40 and A~131 respectively. Among the liquid-based detector technologies, time projection chambers (TPCs) are particularly promising. Both LAr and LXe are excellent scintillators, enabling detectors with low energy threshold. Their ionization response to radiation has been studied for decades and is well known.

We propose to detect nuclear recoils by scintillation and ionization in ton-scale liquid noble gas targets, using techniques already proven in experiments at the 0.01–0.1 ton level. For typical WIMP-nucleon cross sections expected from supersymmetry (10^{-43} cm^2 to 10^{-46} cm^2), the interaction rates are in the range 0.1–10^{-4} events per day per kg of target material. The experimental challenge is to identify these events in the presence of background events from gammas, neutrons, and alphas. These arise from radioactivity intrinsic to the detector and shielding material and cosmic ray muons, the latter requiring the experiments to be run deep underground.

The combined ionization and scintillation signals in the TPCs are rich in information, permitting a very effective separation of β/γ background radiation and multiple-sited, neutron-induced nuclear recoils from single-sited nuclear recoils, which are the expected signature of WIMP dark matter interactions [4, 5]. The separation methods are:

1. **Scintillation to Ionization Ratio.** The primary scintillation signal ($S1$) in a noble liquid TPC is detected by photosensors placed around the active volume. The TPC also produces an ionization signal by drifting the electrons to the top of the liquid volume and extracting them into a gas layer, a "two-phase" configuration. A strong electric field in the gas produces a secondary, drift-time-delayed light signal ($S2$) by electroluminescence. Only the ionization electrons that survive recombination with ions [6] contribute to the ionization signal $S2$. Electron-ion recombination depends very strongly on the ionization density of a track, and it is dramatically different for β's, α's, and nuclear recoils [7–9]. For the more heavily ionizing particles the ionization signal is strongly suppressed. The $S2/S1$ ratio provides a factor of ~200–1000 separation between nuclear recoils and other event types [4, 5].
2. **Position Reconstruction and Fiducialization.** A noble liquid TPC is a homogeneous, 3-D position sensitive device. The drift direction (z) coordinate is measured with sub-millimeter precision by the time difference between the $S1$ and $S2$ signals. The x-y coordinates are reconstructed from the distribution of the $S2$ light over the top array of photosensors, with a precision which varies from millimeters to centimeters, depending on the granularity of the array. Diffusion of the ionization electron during the long drift is negligible in the dense noble liquids [7], preserving precise localization information in $S2$, which is not available in single-phase detectors. Precise event localization is extremely useful for both argon and xenon targets to reduce the residual neutron background via reconstruction of multiple interactions and to reject backgrounds that come from the container walls. In a single-phase detector with 4π optical coverage the $S1$ signals can be reconstructed by exploiting the photon time of flight and/or the intensity distribution of the collected primary scintillation photons, resulting in a much coarser spatial resolution (10 cm or more). This feature is retained as an additional localization method in our two-phase TPC with 4π optical coverage.
3. **Pulse Shape Discrimination.** As discovered by Doke and colleagues, the scintillation of noble liquids depends very strongly on the ionization density of the tracks [8, 10]. Boulay and Hime pointed out that pulse shape discrimination applied to the $S1$ primary scintillation can be very powerful in liquid argon [11], due to a very large decay time difference between the two excimer states (singlet and triplet), which are populated differently by low- and high-density tracks [8]. In argon, the technique has been proven to reject β/γ background by a factor of up to 3×10^7 [5, 12]. The technique is very challenging in xenon due to the similar decay times of the singlet and triplet excimers [7, 8].

For large noble liquid TPCs the bulk radioactivity due to isotopic impurities, present even at exceedingly low levels in the natural targets, can limit the sensitivity to dark matter. One of the main background sources in large argon detectors is ^{39}Ar, a β-emitter produced in the atmosphere by cosmic rays. The specific activity of ^{39}Ar (Q=565 keV, τ=388 yr) is ~1 Bq/kg for atmospheric argon, corresponding to a concentration of

^{39}Ar/Ar=8×10^{-16} [13, 14]. The $S1$ pulse shape discrimination is strong enough to discriminate against the ^{39}Ar activity in atmospheric argon in moderate sized detectors, but event pile-up limits the size of unsegmented atmospheric argon detectors to about 1 ton. Bigger unsegmented detectors can only be built with isotope-depleted material. Such material is now available at moderate cost [15], allowing us to propose a multi-ton argon detector.

Liquid xenon has no short-lived intrinsic radioactive impurities, with the exception of ^{85}Kr. The typical concentration of Kr in commercial xenon gas is at the ppm level. Beta decays of ^{85}Kr (Q=687 keV, τ=15.5 yr) contribute a serious background. For the reduction of ^{85}Kr level to $<$1 ppt, required by the sensitivity goal of a ton-scale Xe TPC, a cryogenic distillation column has been shown to be very effective [16] and has been adopted by the current XENON-100 experiment [17].

The discrimination power, the precision in x, y, and z on the event position, and the effectiveness of chemical purification and cryogenic distillation methods have been successfully demonstrated in published results from Xe and Ar detectors involving many members of this collaboration. The XENON-10 detector [4] with a 5 kg fiducial mass, has set a cross section limit of $<6\times10^{-44}$ cm^2 at 90% CL with a 136 kg·day in LNGS, and has now been succeeded by XENON-100 (50 kg fiducial mass), currently operating at LNGS. The ZEPLIN-II detector (UCLA/UK) with a 8 kg fiducial mass [18] has set a limit of $<6\times10^{-42}$ cm^2 in a 240 kg·day run in 2006, and is now succeeded by the UK ZEPLIN-III detector [19], reaching a sensitivity comparable with that of XENON-10 and similarly undergoing an upgrade. The Princeton group participates in the WARP collaboration and has contributed to the operation of a 3.2 kg Ar prototype reaching a sensitivity of 10^{-42} cm^2 in a 100 kg·day run [5]. This effort has been succeeded by a 140 kg Ar detector, WARP-140, which is now being commissioned and is the largest noble liquid WIMP detector to date. XENON-100 is expected to reach a cross section sensitivity of $\sim10^{-45}$ cm^2 in 7 months of running. The same sensitivity is projected for WARP-140 in a 2 yr run. These experiments will fully confirm the detection principles and the operational feasibility of both Ar and Xe detectors for Dark Matter searches.

The experience gained from all these experiments gives us the confidence to proceed to larger-scale detectors. We propose the construction of ton-scale detectors with sensitivities three orders of magnitude beyond currently published results, capable of setting upper limits of 10^{-47} cm^2 (if no events are seen) or obtaining a scientifically useful number of events at a cross section of 10^{-46} cm^2. Two developments allow larger noble liquid detectors with lower backgrounds than would otherwise have been possible: (1) the recent invention and development at UCLA of a new ultra-low radioactivity photosensor – the QUPID – which has a sufficiently low activity ($\sim$100 times better than the lowest activity PMTs) to be used directly in the proximity of the detector, improving light collection and position resolution and lowering energy threshold; (2) the discovery of underground sources of argon gas low in the radioactive isotope ^{39}Ar (Depleted Argon, DAr) by the Princeton and Notre Dame groups, with the support of the National Science Foundation.

The combination of DAr and Xe detectors, using similar detection principles and operating under similar conditions, can provide clear confirmation of a genuine signal from coherent WIMP interactions. A larger mass is required for the DAr detector to offset the lower cross section in argon per unit mass. With about 50% odd isotopes, natural Xe also permits a search for spin-dependent WIMP interactions.

The DARCSIDE and XENON collaborations have formed a partnership, the MAX collaboration, to submit this proposal for the preliminary design of a DAr TPC with 5.0 ton active (2.7 ton fiducial) DAr mass and a Xe TPC with 2.4 ton active (1.0 ton fiducial) Xe mass, as dark matter detectors for inclusion in the DUSEL ISE program, at the 4850 ft campus. While the DARCSIDE and XENON collaborations are pursuing their own programs for DAr and Xe TPCs in the pre-DUSEL phase, we are joining in a single S4 proposal recognizing the advantages of merging the US dark matter community into a few larger collaborations with the required critical mass and expertise to develop the first suite of DUSEL experiments in a timely and cost effective way. The use of a common engineering team to develop the design of several major subsystems shared by the argon and xenon detectors is intended to realize significant savings in time and cost and will enable an effective sharing of already-tested technologies. In particular, both detectors will make use of the same photosensor technology, electronics, shielding scheme, and purification strategy, and will face similar issues in cryogenics, safety, and underground operation.

We have identified a Project Manager and lead engineers for the design work for the major subsystems (see Sec. XIV). The bulk of our requested funding supports these people and some additional engineers and consultants. Appendix A (in the supplementary materials) specifies the tasks and their managers in WBS form. We summarize the major elements of the WBS in Table I.

The DAr and Xe TPCs will require shielding against external β/γ radioactivity and external and cosmogenic neutrons. Water shielding provides the most cost-effective solution. Our collaboration strongly endorses the effort towards a community-wide engineering of water-based shields and ^{222}Rn-suppressed cleanrooms through a related S4 Proposal (submitted by Princeton University, PI: Frank Calaprice).

Element	Subsystem	Example tasks	Element	Subsystem	Example tasks
1.1	TPCs	Field cage mechanics	1.2	Inner Vessels	Vessel mechanics and seals
1.3	Photodetector	Photosensor testing	1.4	Cryogenic Systems	Cryo cooling systems
1.5	Pre-Purification	DAr extraction	1.6	Runtime Purification	Selection of getters
1.7	Electronics	Design of digitizers	1.8	DAQ	Digitizer readout
2.	Simulations	Neutron background simulations	3.	Shielding/Muon Veto	Design of shield
4.	DUSEL Interface	Facilities interconnects	5.	Radiation Screening	Materials validation
6.	Safety	Hazard analyses	7.	Installation	Procedures
8.	Commissioning	Procedures	9.	Operations	Procedures
10.	E&O	Davis-Bahcall Scholarship			

TABLE I: Summary of major elements of the S4 WBS. Also reported, for each major element, a sample task for illustrative purposes. We refer the reader to Appendix A for the WBS.

III. PHYSICS REACH

The features available to identify a genuine spin-independent dark matter signal are (1) the A^2 factor in the nuclear cross section due to the coherent nature of the interactions [20, 21]; (2) the shape of the recoil energy spectrum for targets with different A [22, 23]. These features can be exploited effectively by operating two detectors of similar sensitivity, but with targets of distinctly different atomic number. Figure 1a shows the recoil energy spectra for Xe and Ar with M_χ=100 GeV and a spin-independent $\sigma_{\chi\mathrm{N}}$=10^{-47} cm^2. Xe is seen to have a greater sensitivity per unit mass than Ar at low energy, but Ar is less affected by the nuclear form factor correction so higher energy recoils can usefully contribute. Combined data from Xe and Ar in combination provide powerful information that can be used to verify the predicted A dependence of both the rate and the spectrum shape [24]. It is also evident from Figure 1a that to achieve similar counting rates, the Ar detector must have a larger fiducial mass.

The DAr TPC (Sec. IX) to be designed in the present work will have a 5.0 ton total (2.7 ton fiducial) target mass. The background rejection from the pulse shape depends critically on the number of photons detected, which depends in turn on the photosensor coverage and the photosensor quantum efficiency [11]. The larger the photo-electron yield, the lower the threshold. The baseline design should achieve a photoelectron yield >7 p.e./keV$_{\mathrm{ee}}$ at null electric field. Monte Carlo simulations indicate that a neutron background of < 0.2 event/yr above the planned 30 keV$_{\mathrm{r}}$ threshold for nuclear recoils is achievable with a conventional shielding scheme and existing photodetectors. The β/γ background, reduced by the use of depleted argon, is expected to be negligible after discrimination (pulse shape and $S2/S1$). For M_χ=100 GeV, the experiment would be able to set a limit $\sigma_{\chi\mathrm{N}}\leq 10^{-47}$ cm^2 or count a few events/yr for a cross section of 10^{-46} cm^2 in a 5-yr run, corresponding to an exposure of 12 ton·yr after fiducialization and accounting for nuclear recoils acceptance of analysis cuts.

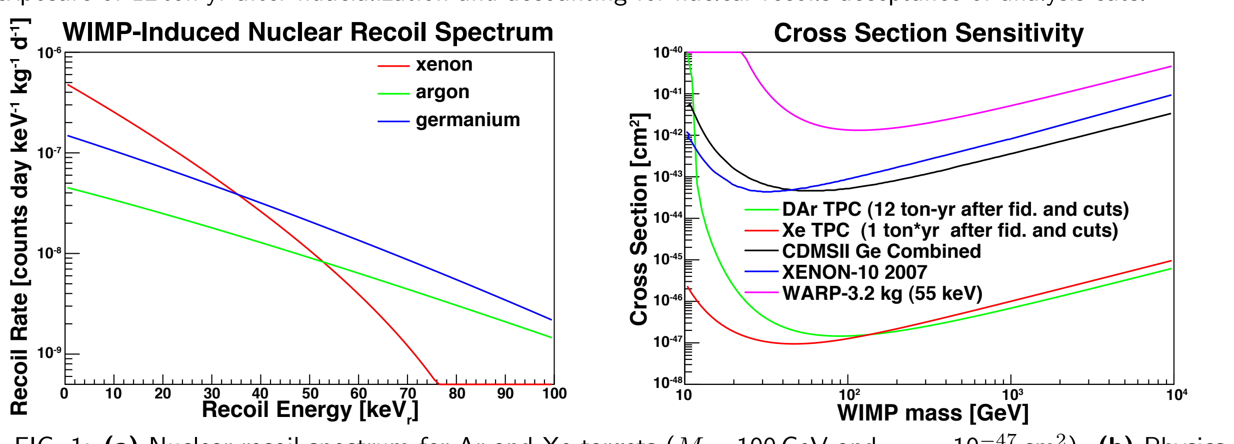


FIG. 1: **(a)** Nuclear recoil spectrum for Ar and Xe targets (M_χ=100 GeV and $\sigma_{\chi\mathrm{N}}$=10^{-47} cm^2). **(b)** Physics reach of the 5.0 ton DAr TPC (5-yr run, 12 ton·yr exposure after fiducial and analysis cuts) and of the 2.4 ton Xe TPC (2-yr run, 1 ton·yr exposure after fiducial and analysis cuts) presented in this proposal, compared with the limits achieved by CDMS, Xenon, Warp, and Zeplin [4, 5, 18, 19, 25].

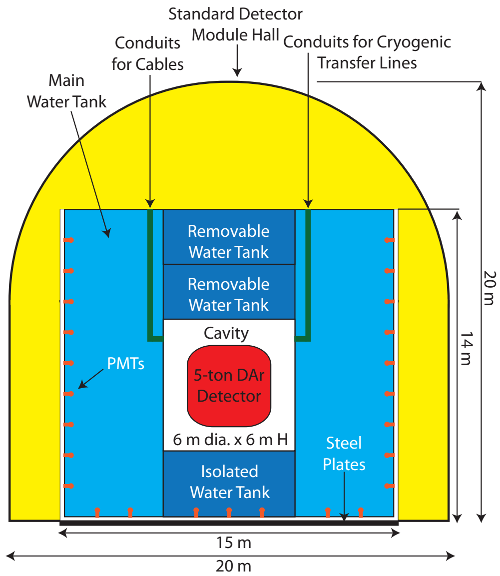


FIG. 2: Water Shielding Tank. The detector will be mounted in a re-entrant tube that serves as an air-filled "detector room" at the center of the tank.

The Xe TPC baseline design (Sec. X) will have a 2.4 ton total (1 ton fiducial) mass and light yield >7 p.e./keV$_{\mathrm{ee}}$ at null electric field, achieved by covering the detector with a 4π array of QUPID photodetectors (see Sec. V below). Based on Monte Carlo simulations, the projected β/γ background is 10^{-7} events/(kg·keV·d) and the neutron-induced background is <0.1 events/yr above the planned 4 keV$_{\mathrm{r}}$ threshold after fiducialization and $S2/S1$ discrimination. This low background is made possible by the use of the novel QUPID photodetectors (see Sec. V below) and by careful selection of the detector materials. The experiment would have a WIMP counting rate of ~10 event/yr for a cross section of 10^{-46} cm^2 and a limiting sensitivity of $\sigma_{\chi\mathrm{N}}\leq 10^{-47}$ cm^2 in a 2-yr run, corresponding to an exposure of 1 ton·yr after fiducialization and accounting for the nuclear recoils acceptance (50%) of the analysis cuts. Figure 1b shows the physics reach of the proposed experiments along with current published limits.

The Xe TPC will also be sensitive to WIMPs interacting through a spin dependent (SD) channel, since natural Xe contains approximately equal fractions of odd and even isotopes. However, as in any SD experiment, the accessible cross section is much larger than for the SI case because the coherent A^2 factor is no longer present and there are additional nuclear coefficients to be included [23]. The sensitivity to SD cross section for the Xe TPC is $\sigma_{\chi\mathrm{N}}\leq 10^{-42}$ cm^2 for pure neutron coupling.

Both the DAr and Xe TPCs will be capable of exploring other possible WIMP scenarios, including the recently suggested model of a dark matter multiplet interacting with regular matter through a light vector boson [26, 27]. The reach of a given experiment is highly sensitive to the galactic escape velocity. However, for a reasonable $v_{\mathrm{esc}} \sim 600$ km/s, the xenon TPC will have sensitivity to $\sigma_{\chi\mathrm{N}}\approx 5\times 10^{-46}$ cm^2 for an inelastic splitting of $\delta=$ 100 keV and M_χ=100–1000 GeV. The argon TPC is robustly sensitive to cross sections of $\sigma_{\chi\mathrm{N}}\approx 6\times 10^{-47}$ cm^2 at δ=50 keV M_χ=100–1000 GeV. Due to the lighter argon mass, the ability to probe the high δ range is highly sensitive to the galactic escape velocity, but is significant with v_{esc}=600 km/s.

IV. NEUTRON SHIELD AND MUON VETO

The primary sources of background external to the cryostats containing each noble liquid TPC are: 1) muons, producing γ-rays and high energy neutrons either in the rocks surrounding the lab or in the shielding material; 2) airborne contaminants such as ^{222}Rn and its daughters and ^{85}Kr; 3) U, Th, and K in the rocks, producing γ-rays and neutrons from fission and (α,n) reactions; 4) U, Th, and K in the shielding material and in the external parts of the detector, producing γ-rays and neutrons.

REQUIREMENTS:

The above background will be mitigated by an external shield, designed to satisfy the following requirements:

1. The external shield must identify cosmic ray muons crossing the shield itself with efficiency >99%.
2. The shield must reduce the external β/γ background in the fiducial region of the TPCs to below 1 events/(kg·keV·d) for the DAr TPC and below 10^{-5} events/(kg·keV·d) for the Xe TPC (This is prior to further background rejection by the methods of Sec. II.) This is to be achieved in combination with supplementary shielding materials in the outer layers of the TPC, and using progressively cleaner shielding material in layers closer to the active target mass.
3. The shield must suppress the large flux of high- and low-energy neutrons coming from the rocks and the flux of high-energy neutrons coming from cosmogenic interactions in the shield itself to less than 0.1 events in the exposures of the experiments after analysis cuts (12 ton·yr for DAr and 1 ton·yr for Xe). This is to be achieved in combination with supplementary shielding materials in the outer layers of the TPC.

WBS SECTIONS: 3.1, 3.2, 4., 5., 6.

Water shielding can provide a cost-effective shield against gamma rays, neutrons, and muon-induced radiation. Standard methods of producing high purity water yield very low levels of U and Th, typically at the level

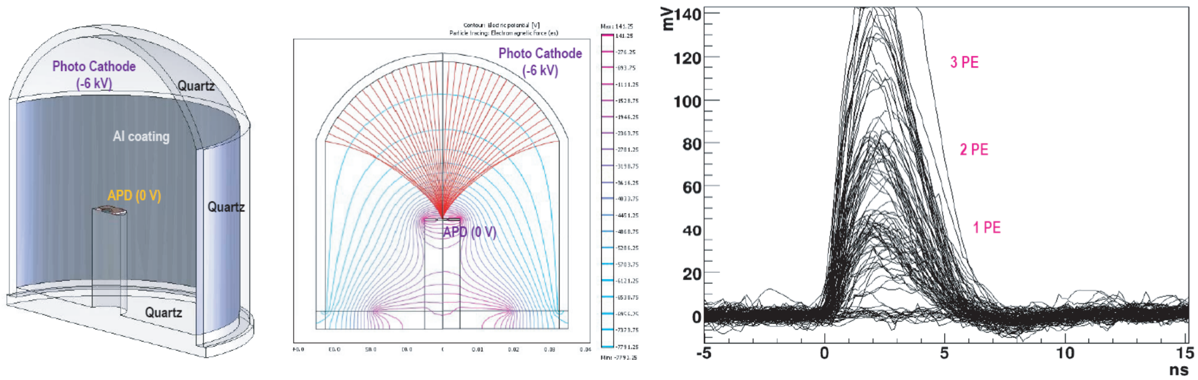


FIG. 3: **a)** Structure of the QUPID. **b)** Electron optics of the QUPID. **c)** Digitized QUPID waveforms: note the separated bands corresponding to detection of 1, 2, and 3 photoelectrons.

of 10^{-15} g/g [28–30]. Radioactivity from a stainless steel water containment vessel is sufficiently low and is mostly shielded by the water or, where needed, by additional shielding in the internal detector structure, so that it has negligible impact on the detector background [31]. The main potential background problem with water shields is ^{222}Rn and its radioactive daughters, especially ^{214}Bi, which emits high-energy gamma rays. Radon contamination can occur due to air leaks or emanation from sealing materials or dirt in the vessel. Avoiding polymer materials with high levels of ^{238}U and high radon diffusivity and using good cleaning techniques can minimize radon contamination.

We foresee the need for independent tanks for the DAr and Xe TPCs. Monte Carlo simulations performed with GEANT4 and FLUKA indicate that 3.0 m of water in all directions, or the equivalent combination of water and steel, is enough shielding to make the neutron background negligible for several ton-years of operation of a detector at the 4850 ft level of DUSEL [32]. However, the Monte Carlos do not correctly predict the rate of high neutron multiplicity events observed in Borexino and SNO [33–35]. Such cosmogenic neutrons may be characterized by a very hard spectrum, which could result in the presence of a more penetrating and dangerous cosmogenic neutron component. A specific activity of a separate community-wide S4 water-shield proposal (PI: Frank Calaprice, Princeton) is to perform a coordinated study of neutron data from existing large underground detectors, to assist in choosing the final water tank dimensions. Our baseline design has a minimum of 4.5 m of water-equivalent shielding on all sides to provide additional assurance against backgrounds not modeled by the current Monte Carlos and to allow future mounting of detectors with substantially larger active volumes in the same water tanks.

Figure 2 shows a water shield for the DAr TPC. The water is instrumented with photomultiplier tubes to tag muons and secondary neutrons from muon interactions in the materials surrounding the active argon volume. The detector is placed in an air-filled cavity within the water shield, capped with removable plugs. This design provides adequate shielding while also solving one of the major safety issues confronting cryogenic detectors in water tanks–the danger of rapid boiling of the cryogen in thermal or direct contact with water in the case of a rupture of one of the cryostat vessels (see Sec. XIII). A design for the Xe TPC, based on the same concept and with the possible addition of a passive lead and copper shield to attenuate γ-rays from the steel of the re-entrant tube, will be developed as part of the S4 effort.

V. PHOTODETECTORS

REQUIREMENTS:

The DAr and the Xe TPC baseline design relies on currently existing photosensors with known characteristics, including radioactivity budget, as summarized in Table II.

WBS SECTIONS: 1.3

The photodetectors required to instrument the TPCs are (along with their electronic bases) among the dominant source of γ-rays and neutrons inside the detector. The success of multi-ton noble liquid TPCs thus depends on the development of ultra-low-radioactivity, high-efficiency photon detectors. To address this challenge, the UCLA group collaborated with Hamamatsu Corporation to invent and produce prototypes of an innovative photon detector, the Quartz Photon Intensifying Detector (QUPID). The QUPIDs are based on a proprietary design and

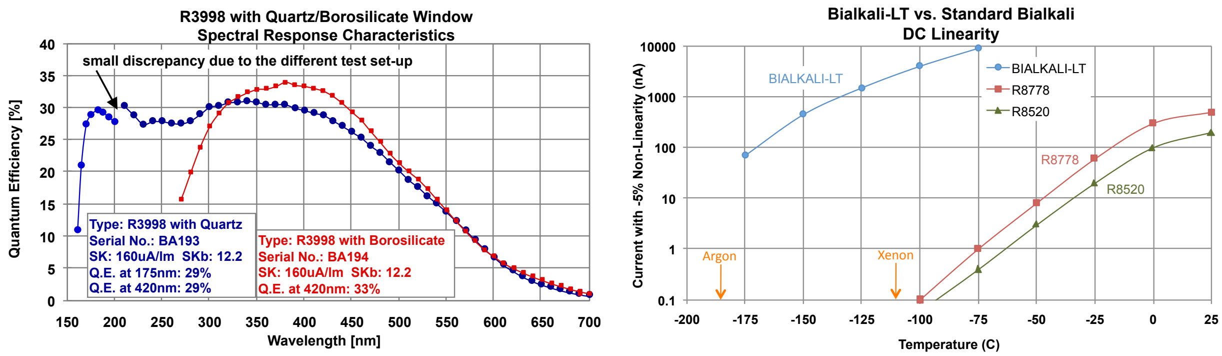


FIG. 4: **a)** Quantum efficiency of the Bialkali-LT photocathode on quartz and borosilicate windows. **b)** DC linearity for the Bialkali-LT photocathode versus temperature, compared with the same quantity for the PMTs R8778 and R8520, equipped with traditional bialkali photocathodes.

their availability is restricted to the MAX program by a MOU between UCLA and the Hamamatsu Corporation. As shown in Figure 3a, the QUPID is a hybrid PMT: photoelectrons emitted from the 3" diameter hemispherical photocathode are accelerated onto an Avalanche PhotoDiode (APD), resulting in a total gain of $2{\times}10^5$ [36, 37]. The QUPID envelope is fabricated from low-radioactivity synthetic fused silica, with good transparency for visible and UV light. This allows direct, efficient detection of the 175 nm xenon scintillation light. These devices can drive several meters of cable without pre-amplification, while preserving very sharp timing characteristics (transit time spread=250 psec, rise time=1.3 nsec, fall time=2.6 nsec, and pulse width FWHM=3.1 nsec). A simple readout scheme can therefore be used, with a linear amplification stage followed by direct digitization of the waveform. Moreover, thanks to the high gain of the electron bombardment, the noise is low and, as a result, clear peaks of not only one but also of two and three photoelectrons can be observed (see Figure 3c).

The first four prototype QUPIDs were screened for radioactivity in a 1-month run in the Germanium-based screening facility dedicated to XENON-100 at LNGS. The radioactivity of the QUPID was too low to be detected above the intrinsic background of the detector, resulting in 95% C.L. limits of ^{238}U<0.49 mBq, ^{232}Th<0.40 mBq, ^{60}Co<0.21 mBq, and ^{40}K<2.40 mBq. These upper limits can be compared to the activity in PMTs used in current dark matter TPCs: ~15 mBq total activity per 2" PMT Hamamatsu R8778, or ~1 mBq total activity per 1" PMT Hamamatsu R8520-06-AL, used in XENON-100. The neutron emission rate from the QUPID (as calculated with the SOURCES package [38]) is less than 10^{-3} $n/(\text{yr}\cdot\text{cm}^2)$, a limit more than ten times better than the rate for the 1" PMT Hamamatsu R8520.

Both TPCs will benefit from use of the QUPIDs. The xenon TPC will have 4π coverage with QUPIDs. In the DAr TPC, QUPIDs will be used to view the top of the detector where their low radioactivity allows use of a thin acrylic window rather than a thick neutron-moderating shield. With this setup, the transverse coordinates of a pointlike event can be reconstructed with sub-cm precision. The very strong $S1$ pulse shape discrimination leads to relaxed requirements on β/γ background radiation, which allows a baseline design in which the sides and bottom are viewed using 8" Hamamatsu R5912-MOD02 PMTs with a specially developed low-radioactivity borosilicate glass envelope (^{238}U=0.4 Bq, ^{232}Th=0.2 Bq, ^{40}K=0.3 Bq, 0.6 $n/(\text{yr}\cdot\text{cm}^2)$). Neutrons from these PMTs can be shielded by 30 cm of acrylic, achieving a dramatic cost savings without important effects on event reconstruction and with only a moderate loss of light. Since neither acrylic nor quartz are transparent to the 128 nm argon scintillation light, the light must be shifted into the visible range by a TetraPhenylButadiene (TPB, peak emission at 430 nm) layer lining the entire active volume.

The photosensors must operate at cryogenic temperatures where standard bialkali photocathodes can have extremely low saturation currents. The standard solution, depositing a thin platinum conducting layer over the photocathode, substantially impairs the quantum efficiency. Hamamatsu has developed a breakthrough "Bialkali-LT" (Low Temperature) photocathode, which operates down to LAr temperatures with high QE. The QE of the Bialkali-LT has already reached 28% (at both 175 and 430 nm) on the quartz faceplate of the QUPIDs and 33%

Photosensor	^{238}U [mBq/unit]	^{232}Th [mBq/unit]	^{40}K [mBq/unit]	Neutrons [$n/(\text{yr}\cdot\text{cm}^2)$]	Photocathode	T Range [K]	QE Achieved [%]	QE Goal [%]
R5912-MOD02	400	200	300	0.6	Bialkali-LT	70–330	33	>35
3" QUPID	<0.49	<0.40	<2.40	$<10^{-3}$	Bialkali-LT	70–330	28	>35

TABLE II: Characteristics and background of the photosensors in the baseline design for the DAr and Xe TPCs.

on a borosilicate faceplate (see Figure 4a). Figure 4b illustrates the difference in saturation current performance at liquid argon and liquid xenon temperature between the Bialkali-LT and a traditional bialkali photocathode. Hamamatsu has agreed to produce both QUPIDs and 8" R5912-MOD02 PMTs with this novel photocathode.

VI. DEPLETED ARGON COLLECTION

FIG. 5: The two stage Vacuum and Pressure Swing Adsorption plant developed at Princeton. The plant was operated on a CO_2 stream producing 0.7 kg per day of depleted argon.

The background discrimination of a two-phase TPC would be sufficient to discriminate against the ~1 Bq/kg ^{39}Ar levels found in atmospheric argon, even for a fairly large detector, provided that the scintillation light is detected with high efficiency to fully exploit the powerful pulse shape discrimination. However, background from ^{39}Ar can cause a loss of live time due to pileup between candidate signal events and ^{39}Ar decays during the electron drift time. This becomes problematic for a two-phase detector with mass >1 ton.

Centrifugation or differential thermal diffusion are established methods for ^{39}Ar/^{40}Ar isotopic separation. However, with very high costs ($40k/kg) and a global production capacity of a few kg/month, these options are not practical for large detectors. Since ^{39}Ar is produced in the atmosphere by cosmic ray interactions on ^{40}Ar, such as ^{40}Ar$(n,2n)^{39}$Ar, one might expect that a source of underground argon which has been protected from cosmic rays for many ^{39}Ar halflives would have a very low ^{39}Ar content. The Princeton group, in a 2-year NSF-sponsored R&D program, has identified two such underground sources of argon-containing gas capable of producing in excess of 30 tons of argon per year, at an anticipated cost of ~$0.5–1.0k/kg for a 5 ton batch.

REQUIREMENTS:

The source and plants selected for the collection of DAr must satisfy the following requirements:

1. The source must contain argon with ^{39}Ar/Ar$\leq 4\times10^{-17}$ (*i.e.*, less than 5% of the ^{39}Ar/Ar in the atmosphere). This will limit the total pile-up fraction in a 5 ton detector to ≈10% and the fractional loss of exposure after software pile-up removal to ≤2%.
2. The plants must enrich the ≤0.1% DAr content of the natural gas stream at the well head to a level 10% by volume or larger, at a production rate of > 20 kg/d of depleted argon.

WBS SECTIONS: 1.5

Preliminary work by the Princeton group with NSF support shows a path toward satisfying Requirement 1. The two underground argon sources identified so far are the National Helium Reserve (Amarillo, TX) and the Doe canyon CO_2 Formation (Cortez, CO). These were sampled during 2008, using a two-stage VPSA system designed by Koch Modular Process Systems (KPMS) and built by Princeton. The collected ~1 kg argon samples were assayed by low level counting, obtaining respective upper limits of 5% and 25% for the ^{39}Ar isotope content relative to atmospheric argon.

The present upper limit on ^{39}Ar/Ar (5% relative to the atmospheric ^{39}Ar/Ar) in gas from the National Helium Reserve already satisfies the requirement for the present experiment. We believe that the ultimate ^{39}Ar/^{40}Ar ratio at both sources could be much lower than this upper limit. Members of the collaboration are building a low-background ^{39}Ar counter with a 1 kg depleted argon target mass that will improve the sensitivity to 0.1% of the atmospheric activity [39–41], and are also pursuing improvements to Accelerator Mass Spectroscopy that may result in measurement of the ^{39}Ar activity with sensitivity below 0.5% of the atmospheric ^{39}Ar/Ar [42–44].

Owners of the gas streams from both sources (Linde USA, drawing crude helium gas from the National Helium Reserve, at its Global Helium plant in Otis, KS; the Kinder Morgan Corporation, owner of the gas mining rights at Doe Canyon) support the MAX efforts towards the extraction of very large batches of depleted argon: see their letters of support attached to in the "Supplementary Documentation" section of this proposal.

The KPMS design study for the VPSA system also addressed subsequent purification of the crude well head stream to 99.999% argon or better, using a 60' cryogenic distillation column with 120 equilibrium stages. This is a conventional method used by commercial firms to produce "research grade" noble gases. A significant engineering effort will be required to design a system capable of producing multi-ton quantities of argon at the source selected for production. It is proposed to sub-contract the engineering for this portion of the S4 work to Linde USA (see their letter of support).

VII. CHEMICAL PURIFICATION OF DEPLETED ARGON AND XENON

DAr and Xe gas require several stages of purification before they are suitable for use in detectors. DAr is extracted from an underground natural gas stream in which the argon starts out as only a minor constituent. This is first refined at the well head into a crude mixture with typical argon concentration $\sim$ 10% by volume, with the remaining fraction largely N_2, CH_4, and He. Cryogenic distillation plants can be designed for operation in a large range of temperatures and for the removal/separation of virtually all gaseous chemical components, and is the most effective method to separate N_2, CH_4, and He from Ar while maintaining a $> 95\%$ recovery of the Ar.

Commercial Xe gas of "research grade" (99.999% purity) typically contains <0.1 ppm of O_2, N_2, and CO_2, water at the 10 ppb level, and Kr at a few ppm level. Some specialty gas companies are equipped to further reduce Kr by a factor of 1,000 using specially designed cryogenic distillation columns at a significant additional cost. Given that purification for Kr-removal beyond this is required for a dark matter search with a ton-scale Xe TPC, it is cost effective to develop a dedicated cryogenic distillation facility, and start with lower cost "research grade" Xe gas.

Under the contract issued by Princeton in 2007, Koch Modular Process Systems (KPMS) performed a preliminary study resulting in a conceptual design for a cryogenic distillation column capable of meeting the distillation requirements for DAr and Xe. Results indicates that it is possible to rely on a single unit to remove N_2, CH_4, and He from Ar, and Kr from Xe, with very high efficiency and meeting the required purification specs. We propose to engineer a single, common cryogenic distillation plant suitable for purification of both the crude argon and commercial Xe with ppm levels of Kr. The cryogenic distillation column will be sited at DUSEL, either above ground or in a shallow underground location.

After reduction of electronegative impurities to the level of 0.1 ppm or better, experience shows that runtime purification with getters (both single-pass and recirculating) is necessary and sufficient to reduce chemical impurities in the detector gas to the levels needed to obtain adequate electron drift lifetime and production and collection of scintillation light. The impurities of greatest concern are O_2, N_2, and H_2O. Electronegative contaminants such as O_2 and H_2O capture electrons during drift and reduce the number surviving to the gas phase [45]. An O_2 contamination <0.1 ppb is required to achieve an electron drift lifetime >1 ms [46], as required for both the DAr and Xe TPC with drift lengths over 1 m. While pure Ar and Xe both transmit their own scintillation, the light can be absorbed by chemical impurities. The MEG collaboration reported that contamination of H_2O in LXe at the level of 100 ppb resulted in a scintillation light absorption length of ∼1 m [47]. Studies by the WARP collaboration using LAr also showed significant scintillation light attenuation in small scale detectors containing ppm levels of N_2 and O_2 [48].

REQUIREMENTS:

The plants and methods for pre-purification and runtime purification must satisfy the following requirements:

1. The cryogenic distillation column must be capable of accepting a crude argon stream (typical argon concentration 10% by volume, major contaminants N_2, He) and producing DAr with 99.999% purity or better, at a rate of 50 kg/day or greater.
2. The same column must be capable of accepting Xe with initial purity of 99.999% or better, and of reducing the Kr contamination below 1 ppt (this level will result in 7 events/(keV·ton·year) from the β^- decay of ^{85}Kr, before $S2/S1$ discrimination and other analysis cuts.)
3. Filters and getters for runtime purification must further reduce all non-noble contaminations to <0.1 ppb.
4. The recirculation rate for the DAr and Xe targets through the in-situ filters and getters must be sufficient to offset any influx of contamination due to outgassing or dissolution, maintaining the concentration of all non-noble contaminants (especially electronegative contaminants) in the targets below 0.1 ppb.

WBS SECTIONS: 1.5, 1.6

For the DAr detector, the baseline design calls for post-distillation purification of the DAr gas by a single pass through a heated Zr-based getter during the initial fill of the storage dewar. Heated-getter systems capable of reducing the concentration of N_2, O_2, and H_2O below 1 ppb in noble gases at flow rates sufficient for the present proposal (15–150 m^3/hr, 26–260 kg/hr of argon), are commercially available [49]. Once the detector itself is filled, the argon is continuously recirculated in a loop which withdraws gaseous argon, passes the gas through the same heated Zr-based filter and activated copper filters, and then recondenses it and returns it to the detector. The copper filter removes O_2 to below 10 ppt. Care must be taken to ensure that the filter-materials are not sources of radioactive contamination [50]. To avoid this, it is possible that charcoal filters followed by a particulate filter will also be needed to avoid streaming of radioactive material from the zeolite.

Purification of the target is expected to be well under control for the argon, due to (1) the very low temperature resulting in an extremely low outgassing rate of O_2 and H_2O from surfaces and (2) data and experience from the extensive R&D performed by the ICARUS collaboration and by the FNAL liquid argon group on argon purification. For example, the maximum electron drift time in the depleted argon TPC, at the baseline drift field of 800 V/cm and with a maximum drift distance of $\sim$2 m, is $\sim$1 msec. In tests at FNAL, drift lifetimes of several msec have been achieved [46] using getter systems as described above.

Similar getter systems also achieve purity levels sufficient to guarantee very low absorption of scintillation light, as seen from recent tests at Princeton. A single-phase liquid argon scintillation detector was built in a cylindrical volume 20 cm tall and 20 cm in diameter (9 kg active mass). The detector volume was delimited on the side by a TPB-coated PTFE reflector and on the top and bottom by 20-cm diameter TPB-coated acrylic windows. Two 8" Hamamatsu R5192-MOD02 PMTs, with 18% quantum efficiency, viewed the active target through the two acrylic windows. The 9 kg active mass was served by a single purification loop along with a larger, 90 kg mass of argon outside the active region. The detector was filled by passing high-purity commercial argon (99.999% purity) through a hot Zr-based getter [49]. This detector gave a photoelectron yield of 5 p.e./keV$_{\rm ee}$. Equipping the detector with Hamamatsu R5192-MOD02 PMTs with the 30% QE Bialkali-LT photocathode should give about 8 p.e./keVee.

Purification issues for charge and light collection in liquid xenon are similar to those in argon, with ppb levels of O_2 and H_2O necessary to maintain the electron lifetime. Maintaining adequate purity of the xenon target is somewhat more challenging than in the case of argon, due to larger impurity vapor pressures at the higher temperature and the stronger solvent properties of LXe. Continuous xenon gas circulation through a high temperature Zr getter has produced $\sim$2 ms electron lifetime in XENON-10 [51], corresponding to 4 m drift length. A 1 ton xenon detector will require sophisticated set-ups for proper bake-out of the different components and may require the higher throughput of a liquid circulation system. The radioactivity of standard zeolites is too high to allow their use in liquid circulation systems such as developed in the MEG experiment [52]. An R&D program focused on methods to improve the purity of detector materials in contact with liquid xenon and to maintain the liquid purity with time will be initiated by the Münster group independent of S4 funding. This group, which has substantial experience in related fields, will study more radiopure zeolites and will test a purification method based on a continuous spark discharge between titanium electrodes [53].

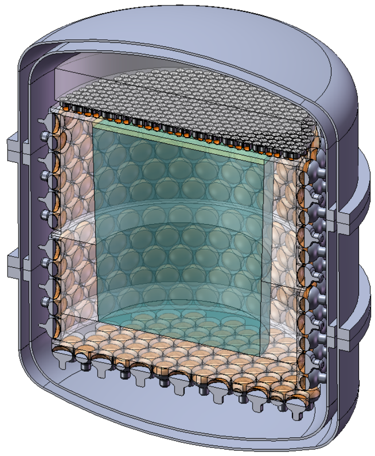
VIII. MITIGATION OF SURFACE BACKGROUND AND CONTAMINATION

Mitigation of surface background is a crucial task for the success of the experiment. Radioactive daughters of ^{222}Rn plate out on surfaces and are the major contributors to surface α activity. Cross sections for (α,n) reactions indicate that one in every 10^6–10^7 α-decay produces a low-energy neutron [54]. α-decays on the inner surface of the detector are particularly dangerous – about half the time, the α goes deeper into the surface, and the daughter nucleus recoils into the active volume, mimicking a WIMP recoil. Surface contamination can be effectively mitigated by locating the last steps of construction and assembly in a ^{222}Rn suppressed cleanroom [55–57]. Such a facility already exists at Princeton University and will make possible the pre-assembly of certain parts of the detectors. The full construction will also require construction of a ^{222}Rn suppressed cleanroom in the 4850 ft campus of DUSEL (see Sec. IV).

REQUIREMENTS:

The surface background will be mitigated by controlling the exposure of the TPC materials during construction. The following requirements apply:

1. All detector surface must be pre-cleaned to remove not only implanted radon daughters but also particulates (another important source of α and β/γ activity) and possible hydrocarbon layers (which would absorb the scintillation photons before they strike the TPB or QUPID).
2. α contamination of inner surfaces must be at or below 10 events/(m^2·d). This contamination level will reduce the unvetoed background induced by surface α's to less than 0.1 counts in the lifetime of each experiment.



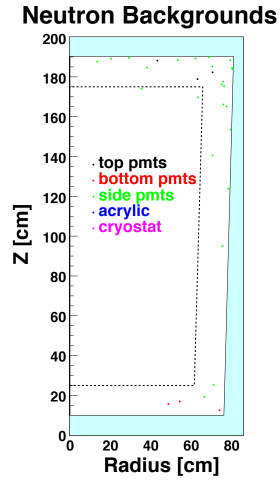


FIG. 6: **(a)** Conceptual drawing of the 5 ton DAr TPC. **(b)** Monte Carlo simulation of the residual nuclear recoil background from neutrons: background events obtained in a 50-yr run.

WBS SECTIONS: 3.3

Requirement 1 is achievable through advanced cleaning techniques developed for Borexino [55]. The cleanrooms at Princeton and at the 4850 ft campus of DUSEL must be equipped with systems to suppress ^{222}Rn activity to 1 Bq/m^3 of air or lower. Exposure of the inner surfaces of the TPCs to air after the last cleaning procedures must be minimized, typically to no more than a few hours. The MIT group will investigate surface alpha reduction for the TPC materials, demonstrate the required reduction factors after cleaning, and determine exposure time limits for detector components. Requirement 2 was met in the construction of the Borexino vessels and the SNO NCD detectors [57].

IX. DEPLETED ARGON TPC

A conceptual drawing of the proposed DAr TPC is shown in Figure 6a. This design is based on concepts that have been developed over many years and have been demonstrated by the successful runs of the Warp, Xenon, and Zeplin chambers and in large single phase TPCs for neutrino detection [4, 5, 18, 19, 58].

REQUIREMENTS:

The DAr TPC must satisfy the following requirements:

1. The TPC will have an active DAr mass of 5.0 ton (2.7 ton fiducial) and a threshold of 30 keV$_\mathrm{r}$ for nuclear recoils.
2. The drift field must be designed to give efficient charge collection throughout the active mass, in particular for α-induced events on the cylindrical inner surface.
3. The 3D position reconstruction of the $S2$ pulses must have a resolution of 1 mm in z (obtained by measuring the drift time) and of ∼1 cm in x and y (obtained by fitting the spatial distribution of the $S2$ photoelectrons detected in the top array of Qupids.)
4. The accuracy of reconstruction of the $S1$ pulses must be ∼20 cm in x,y, and z, and 1 ns in t at the energy threshold (all obtained by fitting the spatial distribution and arrival times of the primary scintillation photons, see Ref. [59].)
5. The reconstruction of the $S2$ pulses must result in a rejection factor for surface α activity of $>10^6$.
6. The TPC must have an $S1$ photoelectron yield in excess of 7 p.e./keV$_\mathrm{ee}$ at zero electric field.
7. The β/γ background in the fiducial region must be less than 1 events/(kg·keV·d) before cuts, then reduced by analysis cuts to less than 1 event in the anticipated 12 ton·yr fiducial exposure of the experiment.
8. The total neutron-induced nuclear recoil background must be less than 1 event in the anticipated 12 ton·yr exposure of the detector. This is obtained by shielding and by applying a set of straightforward analysis cuts such as rejecting multiple interactions and events too near the walls.

WBS SECTIONS: 1.1, 1.2, 1.4, 2., 7., 9., 10.

The DAr TPC will consist of six principal subsystems (see Table III for a summary of dimensions):

(a) The active volume will contain 5 tons of DAr and will be fitted with field shaping structures (drift cathode,

Component	Characteristics	Component	Characteristics
Active Liquid Volume Height	180 cm	3" QUPIDs, Top	745
Gas Height	5 cm	8" R5912-MOD02 PMTs, Bottom	109
Drift Electric Field	800 V/cm	8" R5912-MOD02 PMTs, Side	363
Extraction Field	3.8 kV/cm	Mean Photocathode Coverage	60%
Active Volume Diameter, Top	162 cm	Depleted Argon Mass	5 tons
Active Volume Diameter, Bottom	152 cm	Acrylic Mass	10 tons
Acrylic Minimum Thickness	40 cm	Cryostat Steel Mass	20 tons
Cryostat, Height	380 cm	Cooling Argon Mass	$\sim$10 tons
Cryostat, Diameter	366 cm	Mass of Detector, Full	55 tons
Cooling Power	440 W		

TABLE III: Depleted argon TPC: detector dimensions and other parameters

field cage, grids). These structures drift and extract charge from the liquid into the gas and form a delayed scintillation signal ($S2$) by electroluminescence.

(b) A thick acrylic vessel coated on the inside with TPB wavelength shifter and viewed on all sides by photodetectors will allow efficient collection of scintillation light. The thick acrylic (40 cm on the sides and bottom, 5 cm on the top plus another 35 cm layer above the top QUPID array) is required to moderate neutrons from the side and bottom photomultipliers and from the stainless steel cryostat.

(c) An additional non-instrumented, non-depleted LAr volume surrounding the active volume, plus external cooling plants, will maintain stable cryogenic conditions inside the conventional double-walled stainless steel cryostat.

(d) Purification and recirculation plants (not shown in Fig. 6) will maintain the high purity of the active LAr required to produce strong $S1$ and $S2$ signals.

(e) Electronic support systems will provide high voltages to the TPC and the PMTs; transport, digitize and record the signals from interactions in the active volume; monitor and control experiment parameters; and produce and tag calibration events.

(f) Shielding against neutrons and gamma rays from radioactivity and cosmic ray interactions in the mine rock will be provided by an external, fully contained water shield surrounding the experiment. The shield will also be instrumented as a muon veto.

Requirement 1 is satisfied by design. Requirement 2 will be satisfied by design of the field cage and the configuration of the electrostatic fields in the detector. Requirements 3 and 4 are satisfied by the performance of two-phase noble liquid-gas TPCs in the literature [4, 5, 18, 19]. We performed a full Monte Carlo simulation with the GEANT4 package and verified that the baseline design presented in this proposal can meet these requirements. Requirement 5: our simulations indicate that a fiducial cut at $\sim$10 cm from the walls in the x-y plane provides a rejection factor $>10^7$. A cut in z of 1 cm provides the same rejection for surface events on the cathode of the detector. This rejection is sufficient to reduce surface recoils to less than 0.1 events in the 12 ton·yr anticipated exposure of the detector. Requirement 6 is satisfied by the use of novel and high efficiency photosensors (see Sec. V) and by the use of ultra-high purity DAr (see Sec. VII). Requirement 7 is satisfied by the extremely high $S1$ pulse shape rejection factor for β/γ events available in liquid argon [5, 12], by the use of DAr (see Sec. VI), and by careful choice of materials and shielding that guarantees external β/γ background below 10^{-1} events/(kg·keV·d). In fact, the 10^{-1} events/(kg·keV·d) external β/γ background that can be tolerated by the DAr TPC is relatively high (six orders of magnitude above the 10^{-7} events/(kg·keV·d) background level achieved in the Borexino fiducial volume). This fact will very significantly ease the selection of materials and result in significant cost and schedule savings. Requirement 8 is achieved by the use of radioclean photosensors (Sec. V), by acrylic shielding of the inner vessel, by the use of an external water shield (Sec. IV), and by mitigation of the surface background (Sec. VIII).

The TPC will be built within an acrylic vessel with a liner coated on its inner surface with TPB. The baseline design uses a field cage of 2 mm tall metal rings on 25 mm pitch, inserted in grooves machined in the OD of the liner. Transparent conductive plastic or inorganic films are under study to replace the rings and other field shaping structures to improve the light collection and mitigate possible charging effects. The drift cathode must be supplied with a potential of $\sim$145 kV. The required "High-High Voltage" (HHV) feedthrough from air into liquid argon will be based on the successful 150 kV feedthrough for Icarus T-600 (designed by our UCLA colleagues) [58]; an alternative design has been developed at Fermilab for LAr neutrino detectors. Demountable seals operating at liquid argon temperatures must be provided for the endcaps of the 40-cm-thick acrylic vessel.

Source	Quantity	^{238}U, ^{232}Th	n	n after cuts	β/γ before cuts
		[Bq, total]	[n/yr]	[(12 ton·yr)$^{-1}$]	[ev/(kg·keV·d)]
Water tank steel	100 ton	1200, 400	10^5	$\ll$0.1	$\ll 10^{-5}$
Water	2500 ton	0.25, 0.1*	2.5×10^5	$\ll$0.1	$\ll 10^{-5}$
Reentrant tube steel	25 ton	300, 48	1.3×10^4	$\ll$0.1	2×10^{-5}
Cryostat steel	20 ton	240, 40	2×10^4	$\ll$0.1	0.2
Vessel acrylic	10 ton	0.1, 0.04	2	$\ll$0.1	0.04
^{39}Ar	5 ton DAr	250**	–	–	10
8" PMTs	472	190, 85	10^5	0.3	3
3" QUPIDs	745	<0.4, <0.3	<35	$\ll$0.1	<0.07

TABLE IV: Background sources and background budget for the DAr TPC. The fifth column reports the β/γ background before any cuts (pulse shape discrimination, $S2/S1$, multiple deposition cuts). *Low energy neutrons from radioactivity in the water do not contribute significantly to the background – the 2.5×10^5 n/yr are high-energy cosmogenics. **Beta decays of ^{39}Ar.

Spring-energized O-ring seals have been found to produce acceptable results on small diameter acrylic joints, and it is anticipated that this will work for the larger diameter seals. Similar seals will attach a stainless steel flange carrying feedthroughs for grid and drift cathode high voltages to the acrylic vessel. Photosensors will be mounted to the outside surface of the acrylic with >60% photocathode coverage. The spaces between tubes will be coated with a high-reflectivity film. A thin layer of the non-instrumented liquid argon between the photocathode face and the acrylic vessel acts as an optical coupling.

The total cooling power required for the cryostat will be less than 400 W. Cooling will be provided through a gravity-fed liquid nitrogen loop, supplied by a large storage dewar. In normal circumstances, the nitrogen gas will be re-liquefied with a redundant system of two or more pulse tube cryocoolers. In case of power failure, the nitrogen storage dewar will have enough capacity to maintain system temperature for a minimum of one week. The nitrogen system will be able to provide significant extra cooling power beyond steady-state requirements, for detector filling or emergency situations such as a softening of the cryostat insulating vacuum. Two independent continuous circulation and purification systems will be implemented for the DAr TPC, one for the active argon target (5.0 ton of DAr) and one for the passive argon bath (~10 ton of regular $^{\rm nat}$Ar).

We have evaluated backgrounds from the components of the DAr TPC and from the major components of the external shield with a GEANT4 simulation. Input parameters and results are summarized in Table IV. We assumed that the muon veto efficiency in the external shield is 99%. For β/γ rejection, we assumed the pulse shape parameters measured in Ref. [60] and independently with the WARP-3.2 kg prototype. Multiple nuclear recoils in the active mass were rejected if any two recoils were separated by more than 0.5 cm vertically or 15 cm laterally. External neutrons from cosmic ray interactions in rock and the water shield at the 4850 ft DUSEL level [32] were accounted for. Events that produced recoils within 15 cm from any edge of the active volume were removed by a fiducial cut. The remaining fiducial mass after this cut is 2.7 tons. The β/γ background is reduced to a negligible level, $\ll$0.1 ev/(kg·keV·d), after application of the pulse shape and $S2/S1$ discriminations, preserving a 90% acceptance for nuclear recoils. The simulated residual background after cuts, dominated by nuclear recoils from neutrons, is <0.5 event in the 12 ton·yr exposure anticipated for the DAr detector, see Table IV.

X. XENON TPC

Due to the large atomic number and the coherent A^2 factor in the spin-independent cross section, a fiducial mass of 1 ton of xenon is sufficient to reach a sensitivity of 10^{-47} cm^2 in 1–2 yr. The high density of LXe, about a factor of two higher than LAr, is such that the total active mass of 2.4 ton can be contained in a cryostat of modest dimensions. This also means that a scale-up to a TPC with about 10 times the total mass (20 ton) can be based on the same design strategy to be optimized with the proposed study, with minimal technical changes. The use of the low-radioactivity QUPIDs and of a low activity copper cryostat, will allow us to reach the background required for maximum sensitivity with a minimal LXe for self-shielding, *i.e.* ~10 cm. The baseline design of the proposed Xe TPC, with full coverage of the LXe volume with sensitive photodetectors, results in the maximal use of the fraction of active xenon as fiducial, combining the advantage of a two-phase noble liquid TPC with simultaneous charge and light, with the superior light collection efficiency achieved by a single-phase noble liquid

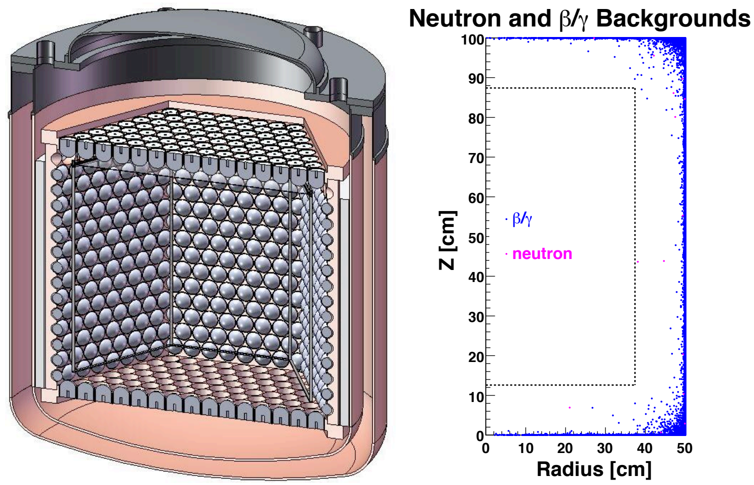


FIG. 7: **(a)** Conceptual drawing of the 2.4 ton Xe TPC. **(b)** Monte Carlo simulation of the residual background from nuclear recoils and β/γ events: backgrounds events obtained in a 10-yr run.

detector. A conceptual drawing is shown in Figure 7a.

REQUIREMENTS:

The requirements for the Xe TPC are similar to those listed for the DAr TPC (see Sec. IX), with these notable differences:

1. The TPC will have an active Xe mass of 2.4 ton (1.0 ton fiducial) and a threshold of 4 keV$_{\rm r}$ for nuclear recoils.
2. The design must minimize the passive Xe mass that gives an $S1$ but not an $S2$ signal.
7. The β/γ background in the fiducial region must be less than 10^{-5} events/(kg·keV·d) before discrimination by $S2/S1$, which is reduced to less than 1 event, after discrimination and all analysis cuts, in the anticipated 1 ton·yr exposure of the experiment.
8. The total neutron-induced nuclear recoil background must be less than 1 event in the anticipated 1 ton·yr exposure of the detector (after fiducialization and other analysis cuts.)

WBS SECTIONS: 1.1, 1.2, 1.4, 2., 7., 9., 10.

The Xe TPC will consist of six principal subsystems (see Table V for a summary of dimensions). They are the same as in the list (a)–(f) for the DAr TPC (see Sec. IX), with these notable exceptions:

(a) The active volume will contain 2.4 tons of Xe.
(b) There will be no inner acrylic vessel between QUPIDs and Xe in the baseline option. The total active Xe is contained in a low activity, vacuum insulated, vessel built largely out of OFHC copper.
(c) Non-instrumented LXe volume is not required for stable cryogenics operation and is kept to a minimum by a special mounting scheme of the QUPIDs.

Requirement 2 will be satisfied by an optimized design of the TPC electrodes structure and electric field cage, using many of the techniques developed and adopted for the XENON10/100 TPCs, including low radioactivity, custom-made grid electrodes and HV feedthroughs. Given the 4π coverage with QUPIDs, an open field cage made with double field shaping wires provides the uniform drift field with minimal charge-insensitive regions. Alternative designs, including one based on a transparent acrylic vessel with a wavelength shifter to convert the Xe VUV light

Component	Characteristics	Component	Characteristics
Active Liquid Volume Height	90 cm	3" QUPIDs, Top	169
Gas Height	5 cm	3" QUPIDs, Bottom	169
Drift Electric Field	1 kV/cm	3" QUPIDs, Side	630
Extraction Field	5 kV/cm	Mean Photocathode Coverage	60%
Active Volume Diameter	100 cm	Active Xenon Mass	2.4 tons
Cryostat, Height	200 cm	Passive Xenon Mass	0.6 tons
Cryostat, Diameter	180 cm	Cryostat OFHC Cu Mass	6.8 tons
Cooling Power	300 W	Mass of Detector, Full	10 tons

TABLE V: Xenon TPC: detector dimensions and other parameters

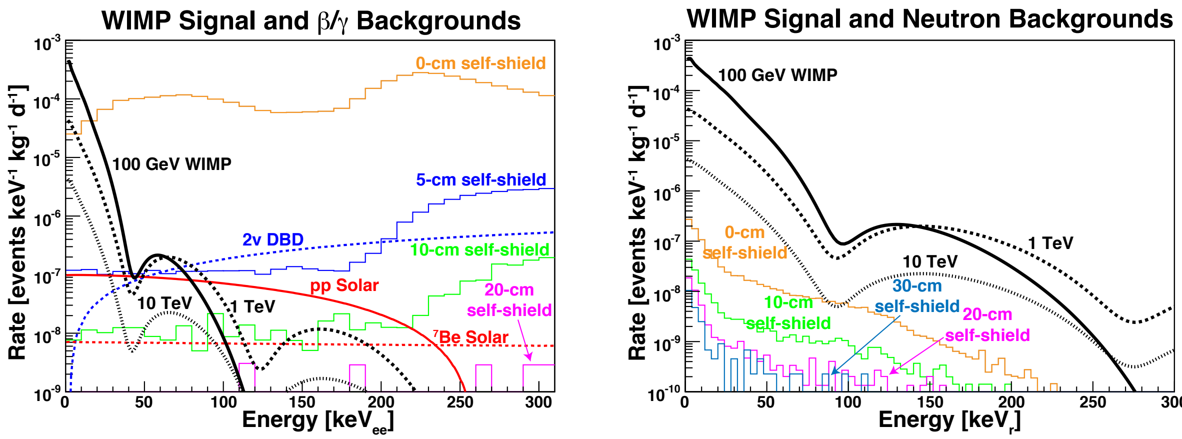


FIG. 8: Expected energy spectra of WIMP interactions, solar neutrinos, two-neutrino double beta decays from ^{136}Xe (assuming τ=10^{22} yr) and gamma ray backgrounds as a function of self-shielding cuts (after $S2/S1$ and multiple-scattering cuts.)

(175 nm) to 430 nm, as in the DAr TPC baseline, will be studied and tested in dedicated set-ups. Requirement 7 will be met by shielding, fiducialization, and proven $S2/S1$ rejection. Requirement 8 will be achieved by the use of a 4π coverage with low-activity QUPIDs to reduce the neutron rate and by applying a set of straightforward analysis cuts such as rejecting events with multiple interactions. As part of the design process, we will study measures to reduce radioactivity from the reentrant tube to the level of that of the QUPIDs and cryostat. In the baseline design this is achieved by adding a passive Cu+Acrylic shielding between the reentrant tube and the cryostat. A second possibility is to build the tube out of acrylic.

The cryogenics system for the Xe TPC will be based on Pulse Tube Refrigerators (PTRs) with temperature-regulated cold-heads. The estimated heat load on the detector, dominated by conduction through signal/HV cables and feedthroughs, is ∼300 W. The PTR currently in use on XENON-100 provides cooling power of 160 W, hence two such units would be sufficient to offset the heat load. Additional or larger units will provide cooling and liquefaction during gas recirculation and filling. The large LXe mass stabilizes the temperature in operating conditions, and the system can be held for very long times at a chosen operating point. XENON-10 and XENON-100 proved temperature stability of ∼1 mK over months using this approach. Even in the case of system failure the inertia of the large cryogenic mass will provide sufficient time to terminate the experiment in a controlled and safe fashion: see Sec. XIII for a description of the planned zero-boiloff, fail-safe recovery system. The considerations on cooling of the detector carry over to the DAr TPC.

The 4π coverage of QUPIDs ensures optimal $S1$ signal detection, with minimum variation with event location within the sensitive volume. GEANT4 simulations indicate a light yield of >7 p.e./keV$_{ee}$ at zero field for 20 m absorption length and taking into account the 50 cm Rayleigh scattering length of liquid xenon. We note that with QUPIDs only on the top and bottom of the sensitive liquid volume and a conventional teflon liner with 98% reflectivity on the side walls, the light yield decreases to ∼5 p.e./keV$_{ee}$ with significant non-uniformity. The main rejection of β/γ background is via the difference in the ratio of ionization to scintillation. The strategy to achieve a multi-ton·year background-free exposure then relies on elimination of the β/γ background by fiducialization of the target. Utmost attention must be paid to any material with even low levels of contamination by gamma or neutron emitters (in particular U/Th) close to the target. We performed a full GEANT4 simulation of β/γ backgrounds, focused on the radioactivity of the QUPIDs, electrons from pp solar neutrinos, and ^{136}Xe 2-ν

Source	Quantity	^{238}U, ^{232}Th [Bq, total]	n [$n$yr]	n after cuts [(1 ton·yr)$^{-1}$]	β/γ before cuts [events/(kg·keV·d)]
Water tank steel	100 ton	1200, 400	10^5	≪0.1	≪10^{-6}
Water	2500 ton	0.25, 0.1	3×10^5	≪0.1	≪10^{-6}
Reentrant tube	25 ton	300, 48	1.3×10^4	≪0.1	≪10^{-6}
Cryostat OFHC	6.8 ton	<0.1, <0.1	<15	<0.1	≪10^{-6}
3" QUPIDs	968	<0.5, <0.4	<45	<0.2	<5×10^{-6}

TABLE VI: Background sources and background budget for the Xe TPC. The sixth column reports the β/γ background before removal with $S2/S1$ discrimination.

double-β decay. We neglect contamination of other detector materials, expected to be negligible compared to the QUPIDs. We also tracked nuclear recoils induced by neutrons from (α,n) or fission reactions in all detector materials. Simulations show that both low energy neutrons from U/Th in the rock and high energy neutrons from cosmic ray muon absorption and spallation can be rejected or attenuated to a negligible level by $>$3 m of active water shield. Table VI summarizes the background estimates. For more details we refer to [24].

Figure 8 shows the expected rate of WIMP signal (for masses of 0.1, 1, 10 TeV and $\sigma_{\chi \mathrm{N}}=10^{-44}$ cm^2), compared with the total γ-ray background rate, and neutron background rate after $S2/S1$ and multiple-scattering cuts. The expected background from pp solar neutrinos and ^{136}Xe 2-ν double-β decay is also shown. The power of the LXe self-shielding is apparent. A cut of only $\sim$10 cm of active LXe is sufficient to reduce the overall background rate below 10^{-7} events/keV/kg/d. Figure 7b shows the spatial distribution of the overall γ-ray and neutron backgrounds in the TPC. With the $\sim$10 cm self-shielding cut, the residual backgrounds are 0.15 γ/yr and 0.13 n/yr, with pp-chain solar neutrinos becoming the irreducible background at a level of 0.5 event/ton/year.

XI. ELECTRONICS & DAQ

The DAr and Xe TPCs present similar challenges for the readout electronics. In both detectors, we need to read out and identify fast signals (a few ns) from QUPIDs and PMTs, with the common requirement of identifying and measuring each photoelectron with similar precision for time and charge, and for event lengths that in both detectors are determined by the drift time and are of the order of 1 ms.

REQUIREMENTS:

The conceptual design for the electronics is common to the two detectors and must satisfy the following requirements:

1. The electronics must be capable of measuring single-photoelectron signals with timing resolution of 1 ns and charge resolution of 0.1 photoelectron.
2. The electronics must introduce no more than 5% deadtime.
3. $S2$ signals from few-MeV γ-rays measured by the top array of QUPIDs could be as large as 10^6 p.e., with a pulse width of 100–1000 ns. With this time dispersion, 16 bits of vertical resolution are required for the FADCs.
4. The electronics must produce a trigger whenever 5 PMTs/QUPIDs are triggered by signals above a threshold of 0.3 p.e. in a window of 100 ns.
5. For the DAr TPC, the electronics must produce a 2^{nd}-level trigger capable of rejecting β/γ events by pulse shape or $S2/S1$ discrimination prior to data transfer.

WBS SECTIONS: 1.7, 1.8

We expect that the argon and xenon experiments can use essentially the same digitizer and trigger boards with relatively small changes in signal conditioning and firmware. There are several commercial digitizers available that may meet our requirements, albeit at a significant cost (see for example, the `V1721` digitizer from CAEN [61] and the `SIS3350` digitizer from Struck [62]). Fortunately, high-speed FADCs (up to 500 MHz) and large capacity Field Programmable Gate Arrays (FPGAs) are widely available today at reasonable cost. We therefore plan to design our own custom board using high-speed FADCs (with a sampling rate of 200–500 MHz) and FPGAs with a large on-board memory.

Requirement 1 can be met by digitizing the PMT and QUPID signals with a frequency above 200 MHz after analog filtering and linear amplification ($\times$10 for PMTs and $\times$50 for QUPIDs). Requirement 2 will be particularly challenging for the DAQ system for the DAr detector: with the expected $\leq$250 Hz trigger rate due to ^{39}Ar and the ~ 1 ms drift time the detector is almost always active. This translates into a more stringent demand on memory and data transfer rate. The maximum drift time of $\sim$1 ms implies that the size of raw data per event per photosensor is $\sim$200k words, which could be zero-suppressed on-board to less than 20k words. Requirement 3 can be satisfied by two FADC chips per PMT/QUPID, each with 10-bit vertical resolution and overlapping ranges (with different input gains) to realize the required 16-bit resolution. The presence of on-board FPGAs enables a variety of triggering and deadtime-free readout strategies, satisfying Requirement 4. Concerning Requirement 5, we remark that the Princeton group operated successfully a 2^{nd} level trigger on the WARP-3.2 kg detector, with a FPGA connected to an ADC digitizing the analog sum of all PMT signals.

One of the advantages of the QUPID is that it does not require a conventional base or resistor chain, which is a large source of radioactivity and heat. For the PMTs in the DAr TPC, several possibilities for the bases are under consideration, including the generation of sets of dynode high voltage levels external to the cryostat and generation of high voltages locally at the PMTs with low-power Cockroft-Walton supplies.

The electronics will also include conventional slow controls to monitor conditions of the experiment. A standard industrial control system will monitor and operate the cryogenics and purification plants.

XII. CALIBRATION

The proposed DAr and Xe TPCs have a significant discovery potential and, in case of detection of a potential WIMP signal, a careful calibration strategy is essential to demonstrate that this is not background. The similar energy ranges and quenching factors for nuclear recoils permit the use of similar calibration schemes for DAr and Xe. Calibration sources of x-rays or electrons, neutrons, and alpha particles are required, interacting both at known discrete locations and distributed through the sensitive volume. The source outputs must be controllable or must lie well outside the dark matter region of parameter space.

REQUIREMENTS:

The calibration system must satisfy the following requirements:

1. To create calibration data demonstrating the electron rejection, a tagged electron source is required. For the argon TPC the source must generate $>10^8$ events in each full calibration run. These events should be produced throughout the sensitive volume.
2. To demonstrate external neutron rejection by analysis cuts, a tagged or at least switchable source of 10–100/sec low-energy neutrons is needed.
3. To demonstrate the reconstruction accuracy and absence of non-statistical tails needed for the $\sim 10^6$ surface α and α-induced recoil rejection requires development of a suitable system of multiple radioactive sources located at known positions in the detector. Source selection for the x-y reconstruction calibration will be investigated with small prototype detectors in the pre-DUSEL program.
4. The sources satisfying the requirements above will also measure the energy threshold and energy response.
5. The Xe TPC will use an optical fiber system to supply light pulses to the TPC for QUPID gain calibration and monitoring using their single photoelectron resolution, and for functional tests after integration. For the DAr TPC, the combination of the reconstruction calibration sources and the uniformly distributed ^{39}Ar will provide sufficient information for monitoring the stability of the detector optics with time.
6. To monitor the electronics pedestal, gain, and non-linearity as a function of time, the sources satisfying the requirements above plus an electronic calibration-event generating system will be developed.

WBS SECTIONS: 1.1.8, 1.1.9, 1.2.2.4, 1.7.7, 7.1, 8.1

Requirement 1 would be satisfied by a pyroelectric crystal generator of penetrating ($\sim$100 keV) x-rays, or by mixing ^{83m}Kr (IT, τ=12.6 hr, 18 and 32 keV electrons and 13 keV x-rays) into the targets [63]. The calibration with ^{83m}Kr is currently being tested in XENON-100. Requirement 2 would be satisfied by either an external or internal/removable d–d generator, or by AmBe source(s) with the Be on a movable shutter. Physics studies and engineering to satisfy requirement 3 will be carried out under the present proposal. Requirement 4 will be satisfied by the sources discussed above. Requirement 5 will be satisfied by the design of an optical pulser system for the Xe TPC, and is otherwise fulfilled by the same sources as for the previous requirements. Requirement 6 will be satisfied as part of the DAQ design under the present proposal.

XIII. SAFETY

WBS SECTIONS: 6

Safety hazards and environmental risks are very similar for the Ar and Xe experiments. Identifying these and engineering means to mitigate them are a crucial part of the proposed S4 effort. Table VII gives a summary of currently identified hazards.

Given the presence of large quantities of liquid cryogens, the most significant potential hazard requiring early attention by designers is related to the structural integrity of the cryostats. The depleted argon TPC will contain 15 tons of liquid argon (5 tons active material plus a 10 ton cooling bath). The total inventory of xenon foreseen for the xenon TPC is 3.0 tons. A rupture disk will provide fail-safe protection of the detector against overpressure. Loss of insulating vacuum in the cryostat would lead to an estimated argon vapor loss rate of 270 m^3/hr. This failure can be mitigated by admitting the gas into a holding tank, backed up by the facility ventilation system in case of a breach to atmosphere. Flooding the vacuum space of the cryostat with water from the shield would generate 12,600 m^3/hr of gas, with a conservative choice of the heat transfer coefficient. The possibility of this

Hazard	Type	Mitigation
Chemicals	Alcohols, acids	MSDS, secondary containment
Electrical	High Voltage (up to 160 kV)	National code
Asphyxiation	Oxygen Depletion	Ventilation
Hoisting and rigging	Crane	Procedure
Ionizing radiation	Calibration sources	Procedure, Shielding
Fire	Electrical, Chemical	Detectors, Suppression systems
Confined space	Tank entry	Procedure
Cryostat Integrity	Mechanical, oxygen depletion	Ventilation
Flooding, drowning	Valve misalignment	Secondary containment, monitoring

TABLE VII: Potential general safety and environmental hazards

failure mode (and the even more dramatic case of uncontrolled mixing between liquid argon and shielding water) can be reduced to essentially zero by using the water tank shielding design discussed in Sec. IV. In this scheme, the cryostat is not in direct contact with the water, but rather sits in a separate, air-filled volume. During the Preliminary Design phase, we expect to work closely with the designers of the DUSEL facility to prepare a full risk-based contingency analysis and mitigation plan, paying particular attention to the critical issue of ventilation.

Both the depleted argon and the xenon TPCs will be equipped with independent zero-boiloff recovery and storage systems, similar to that devised for the MEG experiment [64] and capable of recovering and storing the total inventory of the noble target either in gas phase in high-pressure tanks or in liquid phase in a dewar equipped with redundant active cooling (cryocoolers and a large reservoir of LN_2). The system will be used when emptying the detector. It will also allow the rapid transfer of the noble target to the recovery system in case of problems with the structural integrity of the detector cryostat. In case of problems with the cooling of the detector, the recovery and storage system will allow initial recovery of the excess boil-off from the noble target during the maintenance of the cooling loop.

XIV. PROJECT MANAGEMENT

The Max collaboration is a partnership between two groups of physicists (the DArcSide collaboration and the Xenon collaboration) for the design of liquid argon and liquid xenon dark matter detectors at DUSEL. The collaborations are joining in a single S4 proposal to exploit the substantial overlap in physics reach and engineering of the noble liquid TPCs. Both the DAr and Xe detectors to be designed are two-phase TPCs with simultaneous measurement of ionization and scintillation signals for effective and redundant discrimination of signal from background. Areas of common engineering include photodetectors, electronics and data acquisition, cryogenics, water tank/shielding design, HV and drift-field design, and construction and operation underground.

As well as recognizing common engineering challenges, the formation of this partnership helps ensure that the results of the engineering studies are available for both argon and xenon based experiments. A management structure has been adopted to organize the engineering studies consistent with this philosophy.

The Project Manager responsible for overall workflow and WBS conformance will be Engineer R. Parsells (Princeton University), who will be supported with S4 funds if this proposal is funded. Detector Managers for the DAr and Xe TPC will be respectively Engineer W. Sands (Princeton University, Temple University) and Engineer G. Tajiri (Columbia University), also supported by S4 funds.

Policy questions arising during the course of the S4 project will be decided by consensus of a Project Board, composed of the Max PI and Co-PIs and additional members appointed by the PI, expected to include representatives of National Laboratories, DOE-supported university groups and foreign institutions. If a consensus in the collaboration board cannot be reached, decisions will be made by voting. The Project Board will elect every six months a Chairperson for a single, non-renewable term, alternating representation between Project Board Members with primary interest in the xenon and argon programs.

The DOE OMBE document "PROJECT MANAGEMENT PRACTICES - Work Breakdown Structure (Rev. E June 2003)" states that each WBS item must be a "product". The products of S4 will be engineering design reports describing the dimensions, structure, materials, and possibly method of construction of each item or subsystem comprising the noble liquid detectors under consideration. All items can be classified into those that are wholly or substantially the same for DAr and LXe (class **C**), and those for which the DAr and LXe versions differ substantially, and need to be addressed in a specific way for each of the two detectors (classes **AR** and **XE** respectively). Items of classes **AR** and **XE** will require engineering targeted to the special element in consideration, but in most cases not double the effort since the underlying engineering physics constraints and techniques are similar in the two cases. **See Table I for the major elements of the WBS. See Appendix A, provided among the supplementary documentation, for the full WBS.**

We would like to address several specific topics suggested by the DUSEL S4 solicitation:

Qualifications of team. The MAX collaboration is an international team of scientists actively participating in the currently-leading argon and xenon dark matter experiments (WARP, XENON, ZEPLIN). The collaboration also includes scientists from other successful dark matter experiments (CDMS, DRIFT, COUPP). Several collaborators are from neutrino experiments (SNO, Borexino, MiniBooNE, SuperKamiokande, GERDA, KATRIN). We propose a significant role for Fermilab, where our collaborators have close connections to the liquid argon program for long-baseline neutrino oscillation studies at DUSEL. Collectively, we have expertise in a wide range of relevant experimental techniques and have successfully executed a number of projects of similar complexity and scale. More details on the qualifications of the collaboration will be found in the attached letters of support and biographical sketches.

Anticipated lifetime of the proposed experiment. We propose a 5-year run for the argon TPC and a 2-year run for the Xe TPC. We would expect to be able to construct the detectors over a three year period beginning with the availability of NSF construction funds.

A timeline and budget for the proposed design work. We expect that the Preliminary Design work will be completed within three years of the NSF S4 award. We expect to complete a Conceptual Design Report about one year after the award and a Preliminary Design Report two years later. Our estimates assume NSF funding at the requested level for several university-based groups and subcontracts to industry (see Budget). We will seek additional support from Fermilab and the Department of Energy HEP University Program, with 2.5 FTEs of design effort requested at Fermilab, 0.5 FTE in the UCLA DOE group (PI's Cline and Arisaka) and 0.5 FTE at Princeton (Meyers). During this time period, we expect to proceed in parallel with pre-DUSEL detectors, including the completion of the current and upgraded XENON-100 and WARP-140 programs, as well as the development of a US-based liquid argon program.

Preliminary information on project cost. At present, only very preliminary cost estimates for construction are available. We estimate the equipment costs for the argon experiment to be approximately 16 M$ and the xenon experiment to be 18 M$, both including 30% contingency. A provisional summary of costs is offered in Appendix B.

Description of any limited and targeted R&D. In early conceptual design work we have sought technical solutions that would minimize the amount of R&D required for the Preliminary Design. A small fraction of the S4 resources will be used for studies of surface backgrounds at MIT and development of 8-inch QUPID light detectors in partnership with Hamamatsu (part of the UCLA budget). We expect to continue a parallel R&D effort on advanced detector concepts using other resources and the results of this effort may be exploited to improve the Preliminary Design as warranted. In particular, we note that there is ongoing work on improvements of light-collection and purification at Princeton and Columbia and on transparent electrode structures at Fermilab and UCLA.

Potential for possible future upgrades. We anticipate that the proposed argon and xenon detectors will not be the end of the line for this technology, but rather a practical next step that can be accomplished on a reasonable schedule, with minimal R&D and with only early-stage DUSEL laboratory infrastructure. This project will itself create infrastructure and know-how for the construction of even more sensitive devices. We note that, in particular, that the construction of a plant which produces $\sim$1 ton/month of argon from underground sources would, over time, allow the construction of much larger argon detectors, with low incremental costs.

XV. EDUCATION & OUTREACH, BROADER IMPACT, AND PREVIOUS RESULTS

EDUCATION & OUTREACH: Princeton hosts a summer school for high school students from the Gran Sasso Abruzzo region of Italy [65]. The school, which was initiated by Professors Calaprice and Galbiati in 2003, brings 20-40 students each year to Princeton to study basic physics and to be exposed to the exciting scientific research that is carried out at the Gran Sasso underground laboratory. Physics classes are supplemented with lectures on topics in astrophysics, including dark matter, gravity waves, supernovae, and neutrinos. The school is open to students enrolled in their fourth and fifth years in high schools of the Abruzzo region. Participants are selected on a competitive basis and are provided transportation to and from Princeton, with room and board on the Princeton University campus. Student expenses are financed by the INFN Italian science agency, the regional government of Abruzzo, and through contributions from private groups in Italy and Princeton. Researchers and faculty from Princeton and Italy teach classes and give lectures on a volunteer basis.

With the establishment of the Sanford Laboratory and plans for the Deep Underground Science and Engineering Laboratory (DUSEL) in the Homestake mine of South Dakota, the summer school was expanded in 2008 to include three students from South Dakota [66]. Following a successful first year of the joint program with Italian and American participants, the program will continue in 2009 with ten American students and twenty Italian students. The summer school will provide a rich cultural experience and a unique opportunity to learn about the science and engineering focused on some of the most exciting science in modern times. It will also foster international relationships between researchers and government leaders of both regions that will benefit underground science in both countries.

The American students will be supported by the Davis-Bahcall Scholarships, funded by the 3M Corporation. Named for two great physicists, the Davis-Bahcall Scholarship is intended to spark an interest and promote the exploration of science in South Dakota's young minds. Nobel Prize winner Dr. Ray Davis and Dr. John Bahcall are the two scientists most responsible for the field of solar neutrino physics and neutrino astronomy. Recipients will have the opportunity to spend approximately one month of their summer digging deep into science at the Sanford Laboratory at Homestake in Lead, S.D. and the Gran Sasso National Underground Laboratory in Italy. Participants will also study physics at Princeton University in New Jersey. Coursework will cover a variety of science-related fields, including the subjects of physics, engineering, biology, and geology. Participants will also have the opportunity to interact and learn from distinguished professors from all over the world. College credit is offered to the American students.

As part of the S4 activities, Prof. Keeter of BHSU will focus on integrating the Davis-Bahcall Scholarship with DUSEL in cooperation with the DUSEL E&O team. Other collaboration members will spend a portion of their time teaching in the school.

BROADER IMPACT: There is no doubt that the science question addressed by the MAX experiments has all the ingredients to captivate the interest and imagination of young students and the general public alike. The technologies and methods that will be refined within the scope of the proposed design study will advance the application of noble liquids as imaging detectors in fields outside of particle astrophysics, including national security and medical imaging research. Equally relevant is the impact that this proposal will have in helping the visibility of DUSEL as an international facility, recognized among a distinguished group of underground laboratories worldwide. The MAX project will involve groups from Europe (Germany, Italy, Portugal, Switzerland) and Japan, with an opportunity for them to be part of the exciting development phase of the new laboratory. International cooperation and partnership is not only vital for DUSEL but also essential to achieve the scientific goals of DUSEL in the most cost-effective way and with the broadest involvement of the worldwide scientific community.

PREVIOUS RESULTS: The Princeton group, supported by award **PHY-0503816** and **PHY-0802646** completed commissioning of and operated the Borexino detector, resulting in the measurement of ^{7}Be solar neutrinos and in the first measurement of ^{8}B solar neutrinos with a liquid scintillator target. Supported by award **PHY-0603376**, the Princeton group took part in the WARP-3.2 kg experiment, resulting in the first dark matter search with an argon target [5] and in the WARP-140 kg detector, the largest detector for dark matter searches, currently being commissioned at LNGS. The Princeton and Notre Dame groups, supported by award **PHY-0704220**, conducted the study of underground argon that resulted in the discovery of sources of argon depleted in ^{39}Ar [15]. Other papers recently published by the Princeton group include Refs. [5, 14, 15, 30, 48, 55, 59, 67–78].

Following the conclusion of the XENON10 experiment and publication of its results [4, 51], under under award **PHY-0201740** to Columbia University, the Columbia, UCLA and Rice groups, supported by awards **PHY-0705337** and **PHY-0705326** and by the DOE base grant at UCLA, have focused on the design, construction and underground deployment of a new experiment, XENON-100, aiming at a factor 100 reduction in background over XENON-10 and a ten-fold increase in fiducial mass. Commissioning of XENON-100 has just been completed and the new detector is currently operating at LNGS in the same location and shielding used for XENON-10. A proposal for the XENON-100 upgrade (100 kg fiducial mass and factor of 10 lower background, with deployment of QUPIDs for the top PMTs array) has been submitted to the NSF in Fall 2008, by a larger collaboration, including new groups from Japan, Germany and France.

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