

Direct Detection: Liquid Nobles

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Abstract. Over the past decade, detectors based on liquid noble elements have been at the frontier in the search for WIMP dark matter. They have been shown to powerfully combine low threshold, low background, recoil ID, large mass and self shielding, leading to unprecedented sensitivity to WIMP-nuclear recoil scatters. I will review the current suite of technologies and results to date, and provide an outlook for the coming years.

1. Introduction

The Weakly Interacting Massive Particle, or WIMP, remains a compelling dark matter candidate that could make up the dark halo of the galaxy and be directly detected by scattering from atomic nuclei in a suitable detector. Over the past decade, detectors based on liquid noble elements have been at the frontier in the search for these particles. Several implementations and approaches have been developed and deployed. A common set of characteristics is the combination of large mass targets, low energy thresholds, scalability to increasingly large detectors, and manageable cost. In addition, some implementations also have low intrinsic radioactive background, recoil discrimination, and self shielding.

The deposition of energy in a liquid noble target is shared among three primary channels: atomic excitations that form dimers which de-excite through scintillation light, typically in the VUV or UV; ionization, leading to free electrons that can be collected; and heat, which in the present generation of detectors is not measured. The partitioning of energy among these channels is both complex, depending on energy, electric field and recoil type, and rich with information about the underlying event. In liquid xenon, a recoiling electron deposits most of its energy into ionization, with some going into direct excitation, and little into heat. However, some of the electrons “recombine” with xenon ions to form excited states that feed into the dimer chain, and contribute to the ionization signal at the event site. This first scintillation signal is called “S1.” The recombination is anti-correlated with the strength of the applied electric field. Stronger fields tend to pull the electrons from the event site and reduce the probability of recombination. In Time Projection Chambers (TPCs), the xenon is instrumented to drift the electrons upward through the liquid and extract them into the gas phase (hence the name two-phase detectors). In the gas, the electrons acquire sufficient kinetic energy to generate a second population of excited dimers, resulting in further scintillation light called “S2.” This process of electroluminescence is very efficient, allowing detection of single electrons.

Nuclear recoils in xenon, compared with electron recoils, tend to put a large fraction of energy into heat through ion-xenon collisions. Additionally they tend to produce a higher relative fraction of excitations to ionization, and owing to the tracks being more compact due to higher



stopping power, these recoils have a higher recombination fraction at a given field and energy. The overall behavior is that the S2/S1 ratio is higher for electron recoils than nuclear recoils. This is a critical feature of the xenon detectors because most radioactive backgrounds produce electron recoils (due to Compton scattering, beta decay, etc.) whereas WIMPs are expected to recoil from nuclei via coherent scattering on nucleons. Discrimination factors greater than 99.5% have been achieved.

While liquid argon produces similar S1 and S2, as well as recoil discrimination in the their ratio, a much more power discrimination parameter comes from the time profile of the S1 light, alone. The dimers in liquid noble elements exist in singlet and triplet states. These have different decay times and are populated in different ratios for electron (ER) and nuclear (NR) recoils. This effect is not very pronounced in xenon recoils at low energy, but for argon the times are quite different and easily measured. The argon singlet state decays in 7 nsec and the triplet in 1.6 μ sec. Additionally, about 3/4 of S1 light in NRs is in the singlet but only 1/3 for ERs. Therefore, the relative fraction of non-prompt-to-prompt light is much higher for ERs than NRs. Pulse Shape Discrimination (PSD) of 10^9 have been achieved. Given the presence of the long-lived ^{39}Ar beta-emitter which decays at about 1 Bq/kg, it is this discrimination capability that makes LAr dark matter detectors feasible.

Equipped with these basic properties of LXe and LAr, we turn now to the two main implementations that use these detector media. We'll see some other common features that make the liquid noble detectors so effective for dark matter. One impact is the "detectability" of the signals. First, xenon is intrinsically transparent to its own scintillation light because the first excited state of atomic xenon is at higher energy than the VUV photons from the de-exciting dimers. Second, with sufficiently pure liquid, electrons can be drifted over many tens of centimeters. Together, these effects allow scale up to large linear dimensions, already on the order of a meter. Third, efficient light collection can be made with photomultiplier tubes (PMTs), that are now available with increasingly low levels of radioactivity and high quantum efficiency. Finally, the cryogenic liquid environment is well suited to PMT operation since it is a good dielectric and the low temperature also suppresses dark current from thermionic emission.

In the next four sections of this *proceeding*, I give an overview of the various detector types and collaborations, and refer the interested reader to the more detailed individual papers submitted by speakers of those collaborations, virtually all of which were well represented at the conference. Given that space is limited for those papers, I hope that my overview provides some useful explanatory context when reviewing those detailed and more up to date results. In my overview, I start with two-phase liquid xenon detectors, which have so far given the best sensitivity. I turn then to single-phase argon and single-phase xenon detectors, which emphasize simpler detector geometries, but use only the S1 signal, and then to dual-phase argon.

2. Two-Phase Liquid Xenon Detectors

For dark matter detection, two-phase xenon detectors are implemented as Time Projection Chambers, or TPCs, as depicted in Fig. 1. The signal development proceeds as described above. The S1 scintillation is detected promptly, mostly in the bottom PMT array. Electrons are drifted upward in an electric field and extracted into the gas phase by the gate-anode field, where they produce the S2 light. That light is collected primarily in the upper PMT array. The drifting electrons follow electric field lines and suffer negligible lateral diffusion so they retain information on the lateral $x - y$ coordinate of the event. Using pulse-height weighting or template algorithms of the PMT hit pattern, resolution of about 1/5 of a PMT diameter is achievable. The depth of the event, or z coordinate, is determined by the time difference between the S1 and S2 signals, which is easily resolved in time since the drift velocity is on the order of 100 cm/ms. The 3D position information is a powerful tool for suppression of backgrounds from sources external to the active (drift) region of the detector. In particular, gamma rays

from residual radioactivity interact in the first few centimeters, so knowing the event location allows for a “clean” radio-quiet fiducial region to be established. Likewise, radioactivity from PMTs or from radon daughters deposited on the detector walls during fabrication can also be isolated. Because of its high atomic number and good stopping power, xenon is very effective at self-shielding.

The TPC also images multiple vertex events. WIMPs are intrinsically single scatters, so gammas as well as neutrons that scatter multiply are easily rejected. Tagged backgrounds such as these can also help to measure and normalize background populations to benchmark simulations.

An inherent challenge as detectors are scaled up to take advantage of self-shielding is that external gamma calibration sources are no longer sufficient to probe the behavior at the detector interior. To address this the LUX collaboration developed dissolved sources of ^{83m}Kr and tritiated methane (CH_3T) that are introduced into the xenon stream [1].

The three main xenon TPC programs are the LUX, XENON-100 and PandaX collaborations.

The LUX collaboration has operated a xenon TPC with a 250-kg active region at the Sanford Underground Research Facility, where they (we!) have taken data that sets the best upper limit on the WIMP-nucleon cross section about 6 GeV. See [1] and [2] for updates on more sophisticated calibration and reconstruction techniques that are being used to update the analysis of these 85 live days acquired in 2013, which will push to lower threshold and sensitivity the lower mass WIMPs. LUX continues to acquire data, and is working towards a 300-day exposure before shutting down to replace LUX with the larger LUX-ZEPLIN (LZ) detector [3], which will have a 7-ton active region and about 50 times the fiducial mass of LUX’s ~ 100 kg. LZ will also feature a Gd-doped scintillator shield which will provide a real-time veto as well as in situ monitoring and measurement of the local background. This information will be crucial to demonstrate whether any observed single-scatter nuclear recoils are inconsistent with background.

The XENON-100 collaboration continues to analyze their 2011-2012 data to extract new science results. L. Goetzke reported on their cross checks of possible interpretations of the DAMA results [4]. In one analysis, they checked for leptophilic dark matter and other models that lead to electron recoils. Even with conservative assumptions that artificially lower the inferred DC rate of electron scatters, they rule out axial-vector couplings at 4.4σ and mirror dark matter at 3.6σ . Using their one-year span of data they also carry out annual modulation analysis that excludes DAMA’s favored interpretation by 4.8σ . The XENON collaboration is now deploying a new detector, XENON-1T, which has an expected 1-ton fiducial mass in a 2-ton active region and is in the commissioning phase at Gran Sasso [5]. The surrounding infrastructure will also allow them to pursue plans for a multi-ton detector, XENON-nT.

The PandaX collaboration is running a two-stage program for their first detector, as reported by J. Liu [6]. The initial implementation emphasized a shallow active region for high light collection, and therefore low-threshold, in a 25-kg fiducial region of 125 instrumented kilograms of LXe. They observed 7 events, which were consistent with background (the flat aspect ratio reducing the effectiveness of the xenon self-shielding). These data led to an upper limit that reached to slightly lower WIMP mass than LUX (the lowest at the time for xenon detectors) but still above the best low-mass limit from CDMS. They are now re-commissioning in the same vessel for a 500-kg instrumented mass with a new PMT array, and expect a 300-kg fiducial mass.

3. Single-Phase Liquid Argon Detectors

Single-phase argon detectors have a conceptually-simple spherical geometry that emphasizes 4π PMT coverage for high light collection without the complexity of an electric field for charge drift. At zero field, recombination is maximized so as much of signal as possible goes into S1 light. Together, high S1 production and high light collection give the best performance for pulse

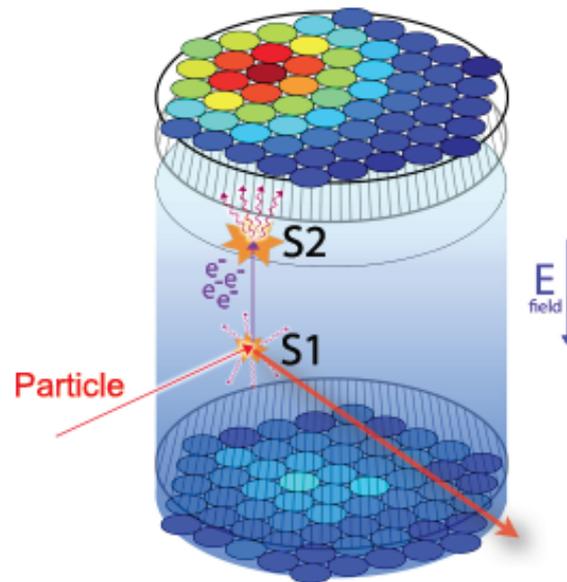


Figure 1. The Time Projection Chamber with two-phase readout consists of a vertical cylinder of liquid with a downward electric field. The field is set up by a cathode wire grid just above a bottom PMT array and a gate-anode grid pair straddling the liquid-gas interface just below the top array. (Courtesy of C.H. Faham.)

shape discrimination (PSD) of electron recoils at as low an energy threshold as possible. As demonstrated by the DEAP collaboration (see the talk by B. Beltran [7]), a factor of two in light collection from 4 photo-electrons/keV to 8, can result in several orders of magnitude in PSD rejection factors. For example, at 60 keV of nuclear recoil energy (equivalent to 15 keV electron recoil), 8 pe/keV gives a PSD of 10^{10} . High rejection factors are essential to keep at bay the high rate of betas from ^{39}Ar decays.

The DEAP detector consists of 3.6 tons of argon in an acrylic vessel surrounded by PMTs mounted on acrylic light guides installed at SNOLab. While high light collection results from this geometry, the lack of an S2 signal means that fiducialization is more challenging because it depends on the pulse shape pattern of the S1 light alone. To reduce the rate from the wall DEAP developed and used a specialized mechanized sander to resurface the interior wall in a low-radon environment. They then coated the interior with TBP, a wavelength shifter that transfers the 120 nm scintillation light to the visible where there is better PMT response. In a three year run these measures are expected to give less than 0.2 background events each from wall events and from electron recoils in the fiducial region at 60 keV nuclear recoil. With this performance, DEAP would surpass existing limits by nearly a factor of ten and is expected also to get the best sensitivity on that timescale from an argon detector. DEAP also described development work aimed at a 50 ton follow up experiment.

The MiniCLEAN experiment, DEAP's neighbor in SNOLab [8], also uses single phase argon but with a different approach. Rather than a single monolithic vessel, MiniCLEAN uses a metal pressure vessel and inserts optical cassettes to define an active region. Their current implementation does not have the scientific reach of DEAP owing to its smaller size (150 kg fiducial in a 500 kg active region) but will demonstrate this approach. Also the cryogenics in this detector allow the detector to run with a neon target to alter the WIMP rate in the detector (lower cross section) while keeping detector background the same akin to "beam off"

data. Because of the detector primarily now serving as a demonstrator, the collaboration plans to run with argon *spiked* with ^{39}Ar to measure the rejection capability required for an even larger detector, that is, factors required for a 150 ton experiment. (Because cross section scales with mass number squared and threshold plays an important role in integrating the recoil spectrum, it is important to use sensitivity projection with clearly stated assumptions when comparing the reach of different types of detectors and target media.)

4. Single-Phase Liquid Xenon Detectors

The XMASS collaboration is carrying out a program with single-phase xenon detectors by instrumenting a (roughly) spherical container of xenon with 4π PMT coverage [9]. Like the argon detectors, they emphasize light collection to set a low threshold. However, in xenon the S1 decay time for the singlet and triplet states do not provide a very strong discriminator between electron and nuclear recoils. Of course, there is also no long-lived high rate of radioactive xenon isotopes to contend with. The approach to improving the sensitivity relies on making the detector from ultra pure materials, removing other radioactive isotopes from the xenon (Kr and Rn), and using the light pattern in the PMTs to identify events in the self-shielding central xenon. In a 835-kg XMASS-I detector the optimized fiducial volume was about 40 kg of xenon with a 40 keV nuclear recoil threshold. This did not obtain a competitive result but much was learned about detector improvements and XMASS is planning larger instruments with a higher fiducial fraction. XMASS 1.5 will aim for a 1-ton fiducial in a 5-ton active region, and XMASS-II could achieve 10 tons in a 25 ton fiducial, and also be competitive for double beta decays studies [10].

5. Two-Phase Liquid Argon Detectors

Two-phase argon detectors combine the features of PSD of S1 in single-phase argon with the S2 of a TPC. At the cost of some added complexity in adding a field cage and high voltage, better position information and S2/S1 recoil discrimination is obtained. The DarkSide collaboration is demonstrating this approach in a detector at the Gran Sasso Laboratory with a 50 kg fiducial volume [11]. To further reduce background they have developed a supply of argon from an underground well which has a 300x reduction in ^{39}Ar . The concentration is lower than atmospheric argon because the production rate from nuclear processes underground are less efficient than than cosmogenic processes in the atmosphere in producing this isotope. See S. Davini's talk [11] for the current results, which include a 50-day exposure with atmospheric argon to demonstrate performance and discrimination, and the first 70 days of a 2-3 year run that is underway with underground argon. DarkSide is also developing designs for a multi-ten-ton scale detector.

The ArDM collaboration [12] is also developing a two-phase detector and has demonstrated good PSD rejection in a 2 ton detector operated in single phase. They will use this detector to test improved light collection using silicon photomultipliers (SiPMs) in a second run that will include a field cage for two-phase operations. Bench tests indicate that the high QE of the SiPMs and low dark current at LAr temperature looks manageable for square-meter arrays for larger detectors.

6. Summary

Liquid noble detectors have made very significant advances in sensitivity to dark matter over the last decade and have dominated the sensitivity reach for masses above a few GeV. While 2-phase xenon detectors have been in the lead, there is activity across several fronts to demonstrate argon detectors, and the ultimate approaches to scaling up, be they xenon or argon. We will hopefully learn in the coming years which of the plans that are now being sketched to extrapolate

beyond existing demonstrations will come to pass. On the argon side, we saw work on ton-scale detectors and R&D to test out ideas to improve scalability (MiniCLEAN’s optical cassette approach and ArDM’s SiPM readout developments). On the xenon front, even beyond XENON-nT and LZ at the multi-ton scale, the Darwin Consortium is studying fundamental questions of background reduction and how clean one can prepare the xenon, and how far one might push ER discrimination to determine if multi-ten-ton scale xenon detectors can push all the way to the neutrino floor. See the talk by M. Schumann for details on work towards a 30-50 ton instrument [13]. I close with Figure 2 — an update to the “Snowmass plot” to illustrate some of these projections. Certainly, liquid noble detectors will play a key role in the coming decade in the search for WIMPs, and hopefully detect them before we hit the neutrino floor.

I’d like to thank my collaborators on the LUX and LZ collaborations. The past 8 years have been a very exciting time, and to learn about and help further develop and test this world-leading technology. I would also like to acknowledge helpful communications in preparing this talk from members of the XENON, DarkSide, PandaX, DEAP, MiniCLEAN, and XMASS collaborations. This work is supported by SLAC National Accelerator Laboratory through DOE contract DE-AC02-76SF00515.

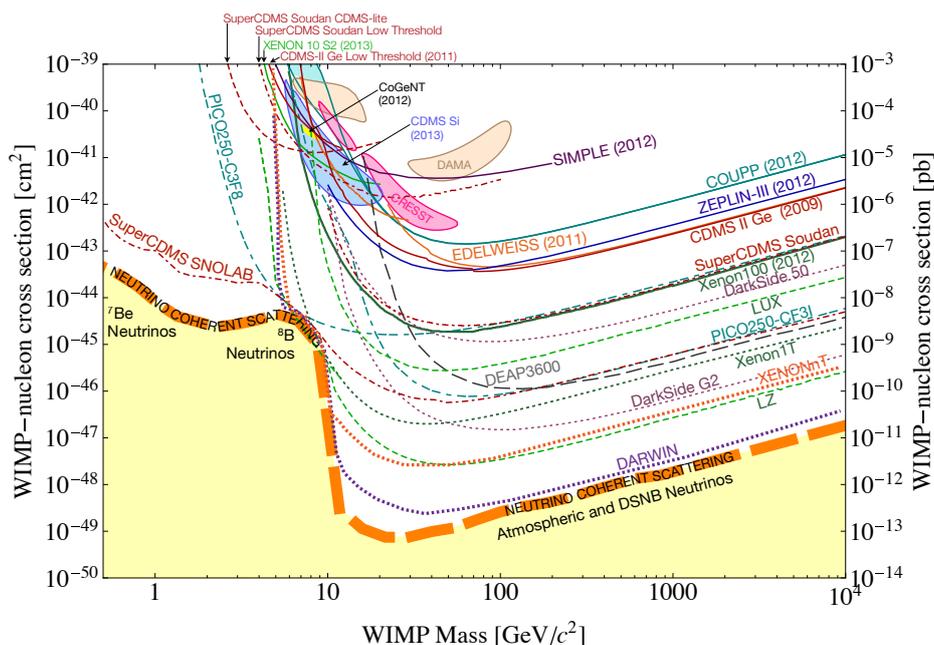


Figure 2. This update of the plot from the Snowmass Workshop [14] is courtesy of L. Baudis. The dashed lines show projections for the various proposed experiments as of 2013. Above about 10 GeV the future results are expected to be dominated by xenon and argon detectors.

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