Versatile Physics with Liquid Xenon Dark Matter Detectors

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Abstract The much-discussed neutrino floor from atmospheric neutrinos will limit the sensitivity to directly search for WIMP dark matter, but is currently still well beyond our capabilities, namely by three orders of magnitude in rate and two generations in detectors. Liquid xenon-based detectors designed to truly probe WIMPs across this parameter range are sensitive to a wide range of physics channels, ranging from dark matter to neutrino physics and touching particle physics, nuclear physics and astrophysics. This contribution puts the current state of the art into perspective and sketches the science that can be done with current and upcoming liquid xenon detectors.

Keywords WIMPs · Dark matter · Xenon · XENON1T · LZ · LBECA · Direct detection · Solar neutrinos · Supernova

1 Context

As evidenced by other contributions to this workshop, the allowed dark matter mass range spans some 80 orders of magnitude, and a multitude of couplings and interaction channels are possible. It is, thus, obvious that a prohibitively large number of experiments is needed to probe the allowed dark matter parameter range in its entirety. Given the current absence of detections, there is thus an urgent need for theoretical motivations in order to prioritize the available parameter space [1]. It is particularly in this context that the WIMP paradigm in all its facets still provides an extremely well-motivated case to search for particles with masses above a GeV or so [2, 3]. Example of interactions come from couplings through the Higgs field, through suppressed weak charges, or even a simple coupling through the Z-boson at loop level, to just name some of the most straightforward hypotheses.

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R. Essig et al. (eds.), *Illuminating Dark Matter*, Astrophysics and Space
Science Proceedings 56, https://doi.org/10.1007/978-3-030-31593-1_12

Increasingly, sensitive detectors are therefore being built to continue probing this WIMP parameter range. In extending their reach, these detectors also achieve better sensitivity to signals from other dark matter models such as axions and axion-like particles or dark photons. Furthermore, neutrino-induced signals of various origins become measurable. Even the search for neutrinoless double-beta decay becomes feasible using the same detectors. Thus, these experiments turn from single-purpose dark matter searches into observatories for particle, astroparticle and nuclear physics.

By far, the most successful detector technology to search for direct interactions of WIMPs particles is liquid xenon-based time projection chambers (TPCs), as pioneered by the XENON10 collaboration [4] and subsequently improved upon by the XENON100 [5], LUX [6], Panda-X [7] and XENON1T [8] collaborations. Future experiments such as LZ [9] and XENONnT [10] continue this programme, with a generation-3 detector, sometimes called DARWIN [11], on the horizon. Such a generation-3 detector will not only probe the entire accessible WIMP parameter space down to the signal from atmospheric neutrinos, but will also be a multichannel experiment with a versatile and exciting physics programme.

2 Liquid Xenon TPCs: Redundancy Is the Key to Success

For a direct dark matter search, the expected energies are very low, of order keV or even less, with a spectrum that is a falling exponential with energy. Thus, the sensitivity can be increased by going to the lowest energies allowed by the detector. As there is less energy deposited in the detector, the signals become smaller, and one simply runs out of information. This makes it hard to distinguish signal from background, where background is not only from environmental radioactivity but more importantly from instrumental artefacts and various processes happening at the quantum limit of the detector. In fact, over the past decade or more, none of the leading WIMP searches were truly limited in sensitivity by the expected background from environmental radioactivity, but rather by detector-specific artefacts such as dark counts, imperfect signal collection near surfaces or specific event topologies in the detector. Whereas, radioactive backgrounds are simulated ahead of time and care is taken in the construction of the experiment that they can be dealt with at the level required for the projected sensitivity, instrumental artefacts are much harder or impossible to predict and thus readily are the limiting factors. The key to extending the reach of a detector is therefore its ability to distinguish true dark matter-induced signals from other, often unexpected detector artefacts.

This challenge is ideally met by liquid xenon TPCs through a single, monolithic design, paired with redundant readout even at threshold. For an educational description of these experiments, the reader is referred to the Wikipedia articles on LUX [13] or XENON [12]. The monolithic design not only reduces the surface-to-volume ratio and thus the relevance of instrumental artefacts. Crucially, this large volume allows cross-checks that would otherwise be hard or even impossible. For example, neutron-induced nuclear recoils have long thought to be an indistinguishable signal in any

WIMP detector. This is not true for the large TPCs now being used: neutrons will tend to scatter multiple times. Thus, by measuring nuclear recoils with high multiplicity, one has an in situ measurement of the neutron flux and thus, via simulation, a measurement and limit on the allowed single scatter background from neutrons.

The second key feature of this technology lies in the redundancy of the extracted information from each event, even at threshold. For example, the vertical (z) coordinate of an event is measured by the drift time of the event, but in addition, it is also encoded in the width of the ionization ($S2$) peak, and even in the hit pattern of the scintillation light ($S1$). Requiring consistency between all these redundant parameters is a powerful tool to reject detector-specific artefacts, such as events happening in the gas phase, or low-energy events originating from accidental pile-up of individual photomultiplier dark counts and photoionization events, just to name some examples. Another simple example includes the fact that not only the sizes of both scintillation ($S1$) and ionization ($S2$) signals need to be consistent with a given signal (e.g. of low energy for a generic WIMP), but also their ratio has to satisfy that expected of nuclear (or electronic, depending on the model) recoils.

3 A Generation-3 Experiment Is Required or: The Atmospheric Neutrino Floor Is Far, Far Away

Recently, the process in which an incoming neutrino scatters off a target and induces a nuclear recoil was discovered [14]. Direct WIMP search experiments are scattering experiments and as such only sensitive to the transferred momentum. This leaves a degeneracy between the signal induced by heavy but slow WIMPs, on the one hand, and light but relativistic neutrinos via coherent scattering off the nucleus on the other. Thus, neutrino-induced signals from astrophysical sources can be plotted in the same parameter space as the usual WIMP limits [15].

Two such signals need to be discussed separately: One is that of solar boron-8 neutrinos which look similar to ~8 GeV WIMPs. This is an exciting signal that XENON1T or at the latest LZ and XENONnT will be able to measure. This signal will be the first measurement of neutrino physics using a dark matter detector with consequences for solar astrophysics and the solar metallicity problem. Concerning the search for WIMPs, this signal will be a welcome in situ calibration line at the lowest energies.

The other signal comes from atmospheric neutrinos. This signal is still about three orders of magnitude beyond the sensitivity of current experiments. Even the current-funded experiments LZ and XENONnT will not be able to probe the available WIMP parameter space down to this signal. Thus, there is a very strong motivation to pursue a larger and more sensitive liquid xenon detector. Such a generation-3 experiment will be able to probe the entire accessible WIMP parameter range down to the signal from atmospheric neutrinos while simultaneously providing opportunities for many other measurements, from other dark matter signals to neutrino physics including the search for neutrinoless double-beta decay.

4 From WIMPs to Dozens of Science Channels

Thanks to their low-energy threshold, low background, large exposures and interesting target material, liquid xenon TPCs more and more turned into versatile science machines. Low-energy nuclear recoils can be interpreted in terms of spin-independent [6–8] or spin-dependent [16] interactions; more generally using effective field theory [17] or more specifically assuming light mediators as in the case of self-interacting dark matter models [18]. Those searches can be pushed to reach lower masses [19, 20] or much higher masses reaching even up to the Planck scale [21].

The extreme self-shielding in liquid xenon reduces the low-energy background by four–five orders of magnitude. This makes even the electronic recoil background very interesting to search for signals from dark matter. A particular interesting newly proposed [22] channels is through the Migdal effect, where inelastic scattering from low-mass WIMPs results in an electronic recoil above threshold [23]. Searches have been published for axion-like particles [24], SuperWIMPs and dark photons [25] as well as solar axions [26], leptophilic WIMPs [27], bosonic superWIMPs [28], mirror dark matter [29] and WIMPs scattering inelastically off the xenon [30].

Further very interesting signals come from the neutrino sector. For one, there are the above-mentioned future astroparticle measurements of electronic recoils from pp solar neutrinos, nuclear recoils from solar boron-8 neutrinos, as well as atmospheric neutrinos [15]. Neutrinos also provide the means to probe other physics beyond the standard model, for example through signals from sterile neutrinos or neutrino magnetic moments [31]. See, in particular, the contribution by Roni Harnik on chapter ‘Interplay of Dark Matter Direct Detection and Neutrino Experiments’ for more on these possibilities. Should a supernova goe off anywhere in our Milky Way, already running xenon experiments are sensitive to the nuclear recoils from such supernova neutrinos [32]. Double-electron capture has been searched for using the XMASS detector [33] with a sensitivity that can be improved upon with XENON1T. Finally, future liquid xenon dark matter detectors will also be competitive to search for neutrinoless double-beta decay [11].

5 The LBECA Approach

Thermal relic particles in the MeV–GeV mass range are another interesting target. Directly probing this mass range has been pioneered using LXe detectors [34] but hit previously ignored background sources at the level of individual or several electrons. While some sources of these few-electron backgrounds have been identified, others remain mere hypotheses, and methods to eliminate them are lacking. The LBECA collaboration has been formed to tackle this issue by identifying the various backgrounds and reduce them through dedicated changes to the detector hardware. The goal is to realize a dedicated, small detector that can overcome the major background sources and will feature an improved sensitivity for such low-energy signals.

6 Outlook: A Request to Theory

There are two simple cases for the future of this field. One, a detection of dark matter particles would be established by the current suite of experiments. In this case, the path forward is clear, namely to measure the properties of the underlying particle, its velocity distribution, couplings, etc. The other path is the more interesting one to be thinking about now: What if the currently experimental suite will not identify a dark matter particle, even in the next decade? Which experiments should one design and build then? Which will be the most well-motivated candidates that should be probed, and how would one go about it?

The dark matter motivation is not going anywhere, and if anything, the identification of particle candidates is only becoming more pressing. Thus, irrespective of the technical obstacles that may preclude realization of a given proposed search in this decade, the motivation to build an appropriate experiment will become better stronger and stronger. New technologies should be expected to push the limits of what is currently possible, in turn requiring a significant period of R&D. This development can be anticipated today: In proposing new well-motivated particle hypotheses and techniques to test them, one can lay today the foundation of a desirable experimental programme for years to come.

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