Dark Matter Detection and the XENON Experiment

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1 Abstract

Observations on all fronts strongly support the view of a universe composed of >96% invisible matter and energy. The invisible matter is non-baryonic, cold and likely in the form of new particles generically referred to as Weakly Interacting Massive Particles (WIMPs), relics from the early universe. One way to detect WIMPs is to measure the nuclear recoils produced in their rare elastic collisions with ordinary matter. The predicted interaction rate ranges from the best sensitivity of existing experiments of ∼1 evts/kg/yr to ∼1 evts/1000 kg/yr. Experiments based on noble liquids offer the potential to meet this sensitivity goal, with a combination of large target mass and excellent background rejection at reasonable cost. After a brief overview of the approaches used for dark matter direct detection, I will focus on the recent performance and current status of the XENON experiment.

2 Introduction

The nature of dark matter and dark energy, which compose >96% of the universe (see [1], and references therein), is one of the most fundamental questions in physics. The leading candidate for the invisible "dark matter" is relics from the early universe known as Weakly Interacting Massive Particles (WIMPs). Such particles are also predicted by extensions of the standard model of particle physics, such as Supersymmetry (SUSY) [2]. If WIMPs exist, they are also the dominant mass in our own Milky Way, and, though they only very rarely interact with conventional matter, should nonetheless be detectable by sufficiently sensitive detectors on Earth.

In direct detection, one measures the energy, typically a few tens of keV [3], of the nuclear recoil which results from a WIMP-nucleon elastic scattering. A variety of target nuclei and detectors are used in direct detection experiments worldwide.

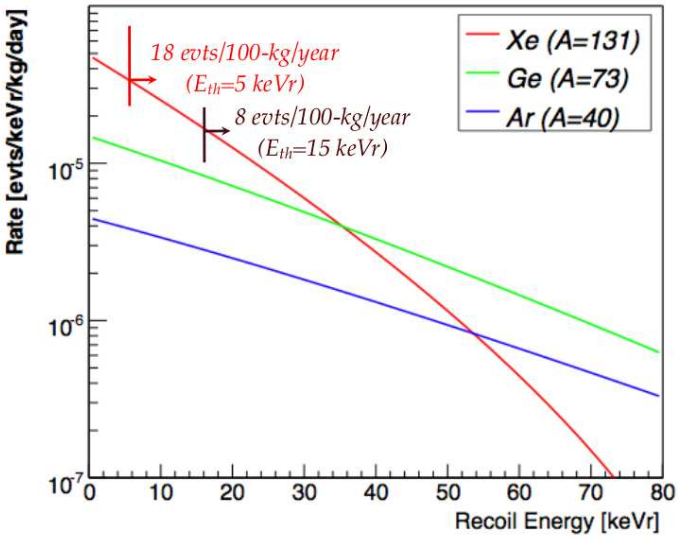

Figure 1: Event rates for a 100 GeV/c^2 WIMP with spin-independent WIMP-nucleon cross-section of 10^{-44}cm^2 for different target materials.

For a recent review of the field we refer to the report by the DUSEL S1 Dark Matter Working Group ([4], and references therein). Covering the bulk of the SUSY parameter space for WIMPs will require a sizable increase in sensitivity from the current best experimental limits [7, 6]. An increase in detector mass and exposure, in addition to a reduction in and/or improved rejection of radioactive and cosmogenic backgrounds is necessary.

The predicted event rates for a WIMP mass of 100 GeV/c^2 and a spin-independent WIMP-nucleon cross-section of 10^{-44}cm^2 are shown in Fig. 1 for Ge, Xe and Ar targets. The fast fall of the event rate with increasing recoil energy demands a very low energy threshold, around 10 keV. At this energy, the event rate for a Xe target is about 30% higher than for a Ge target, due to the Xe larger atomic number. Cryogenic solid state detectors, based on Ge and Si crystals, have for a long time dominated the field of dark matter direct detection, showing the best background discrimination and reporting stringent spin-independent WIMP-nucleon cross-section (4.6×10^{-44}cm^2 at a WIMP mass of 60GeV/c^2 [7]).

In recent years, however, the application of cryogenic noble liquids in dark matter searches, has gained new momentum due to their promise for large target mass detectors with possibly as powerful background discrimination as cryogenic crystals. LXe and LAr are especially attractive as they are known to be good scintillators and ionizers, as established in many works. The scintillation mechanism in these liquids is well known [8]. Both excitation and electron-ion pairs recombination produce excited dimers, which lead to scintillation light ($Xe_2^* \rightarrow 2$ Xe + $h\nu$ in the case of Xe). In pure liquids, the light pulse has two decay components due to de-excitation of singlet and triplet states of the excited dimers. These components have decay times which depend strongly on the ionization density of the particle. For alpha-particles in LXe the shorter decay time produced from the de-excitation of singlet states and the longer one from the de-excitation of triplet states, are 4.2 and 22 ns. However, the scintillation for relativistic electrons has only one decay component whose effective decay time is 45 ns. This is due to the slow recombination between electrons and ions produced by relativistic electrons, since this component disappears if some electric field is applied. The decay shape of scintillation light from energetic electrons in LXe, under an electric field of 4 kV/cm, has the usual two decay components, with the short one being 2.2 ns and the longer one being 27 ns. In LAr, these components have decay times which are much more separated, allowing for an easier pulse shape discrimination (PSD) of the scintillation signal as background rejection tool. The ionization electrons which escape recombination can be collected with an applied electric field. The recombination process strongly depends on the ionization density of the radiation and its track structure, so that the ratio of ionization to scintillation in noble liquids is different for electron recoils from gamma and beta background and for nuclear recoils from WIMPs and neutron background. The simultaneous detection of charge and light therefore provides background discrimination in LXe and LAr, in a similar way as the simultaneous detection of charge and phonon signals provides discrimination in cryogenic Ge and Si. In addition to being available in large quantities for cost effective large volume detectors, another advantage of LAr and LXe over cryogenic solid state detectors is their high boiling point, 87K and 165K respectively, which require much less complex cryogenic systems.

I will briefly review the XENON experiment which is based on the simultaneous measurement of charge and light in a Xe two-phase time projection chamber (TPC).

3 The XENON Dark Matter Experiment

The goal of the XENON Dark Matter phased program is to realize a very sensitive, low background, dual-phase TPC containing 1000 kg of Xe as fiducial target, to search for both spin-independent and spin-dependent coupling of WIMPs with matter. With an energy threshold of 5 keV, nuclear recoil equivalent, and a total background event rate lower than 10^{-4} evts/kg/keV/yr before any rejection, the sensitivity goal of XENON1T is at the 10^{-47} cm^2 level, or almost four orders of magnitude lower than the current best sensitivity (see Fig. 4).

In the XENON Dark Matter experiment, the simultaneous detection of ionization and scintillation in a liquid xenon 3-D position sensitive time projection chamber is used to identify nuclear recoils, produced by WIMPs (and neutrons), from electron recoils produced by gamma and beta background, with a rejection power better than 99.5%.

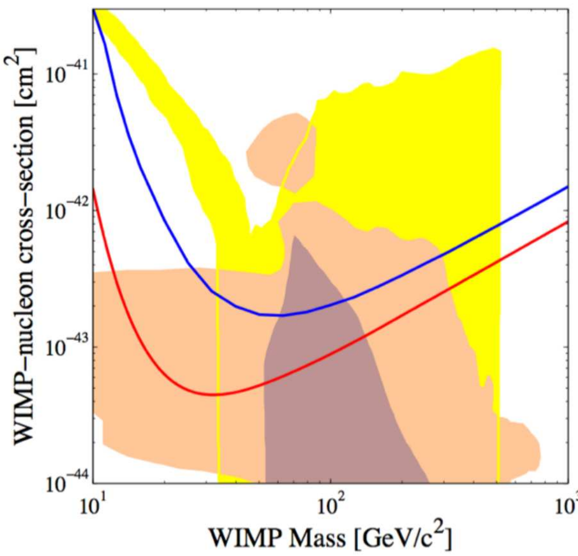

Figure 2: Spin-independent WIMP-nucleon cross-section upper limits (90 % C.L.) versus WIMP mass. Shown curves are for the previously best published limit (upper, blue) and the current work (lower, red). The shaded area is for parameters in the MSSM models (yellow), the Constrained MSSM models (marron) and CMSSM with the recent improved Standard Model prediction for the branching ratio of $\overline{B} \Rightarrow X_s\gamma$ (brown).

The first prototype detector, XENON10, was deployed at the Gran Sasso Underground Laboratory (LNGS) [9] in Spring of 2006 and the first results from a WIMP search were obtained in Spring 2007, making it the most sensitive dark matter experiment worldwide. Fig. 2 shows the 90% C.L. upper limit on the spin-independent cross-section of a WIMP with nucleons of $8.8 \times 10^{-44}\mathrm{cm}^2$ for a WIMP mass of 100 GeV/c^2 [6]. The result is based on 58.6 live days, acquired between October 2006 and February 2007. The same data were also analyzed for spin dependent coupling of WIMPs to matter [10]. The result for pure neutron couplings are the world's most stringent to date, reaching a minimum cross section of $5{\times}10^{-39}\mathrm{cm}^2$ at a WIMP mass of 30GeV/c^2 (Fig. 3).

The excellent performance of this first generation TPC has enabled the LXe technology to be at the forefront of dark matter direct detection and the renewed XENON Collaboration is currently pursuing an aggressive second phase of the program with the XENON100 experiment.

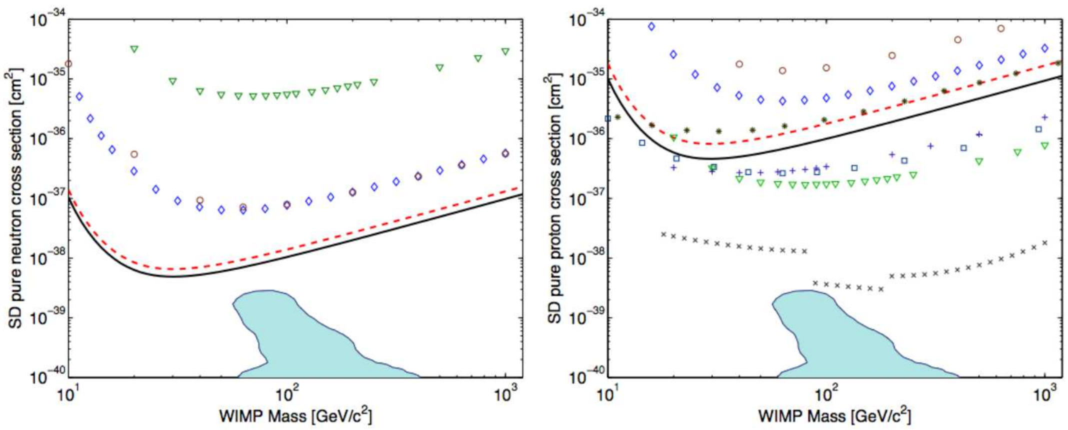

Figure 3: Combined 90% CL exclusion Limits for Xe^{129} and Xe^{131} for pure neutron (left and pure proton (right) couplings (solid curves). The dashed curves show the combined Xe limits using the alternate form factor. Also shown are the results from the CDMS experiment (diamonds), ZEPLIN-II (circles), KIMS (triangles), NAIAD (squares), PICASSO (stars), COUPP (pluses) and SuperK (crosses). The theoretical regions (constrained minimal supersymmetric model) are also shown.

The sensitivity reach of the XENON100 experiment is a spin-independent cross section of $\sim 2 \times 10^{-45}$ cm^2 within 2009 (see Fig. 4). Following this phase at the 100 kg scale within the phased XENON program, the next step is the realization of the XENON1T TPC, to be operational by 2013 with the projected sensitivity shown in Fig. 4. We have started a design study for the tonne scale experiment, with which we will probe the lowest spin independent WIMP-Nucleon cross section predicted by SUSY.

The XENON100 detector is a dual phase TPC, in which ionization electrons produced by an event in the liquid xenon are efficiently extracted from the liquid to the gas, with subsequent amplification via proportional scintillation. The ratio of the amplitude of the charge and light signals, being quite distinct for nuclear and electron recoils, provides the basis for event-by-event discrimination in the XENON concept. A schematic of the XENON100 TPC is shown in Fig. 5. The XENON100 detector consists of an inner target surrounded by an active LXe veto. Both target and veto are contained in a single double-walled vacuum cryostat made of low activity stainless steel (SS). The total mass of Xe required to fill the detector is 170 kg, of which approximately 70 are in the fiducial volume (target). The light readout is based on the same type of 1 inch square photomultiplier tubes (PMTs) as used in XENON10 (Hamamatsu R8520-06-AL), but with selected low radioactivity materials. The target

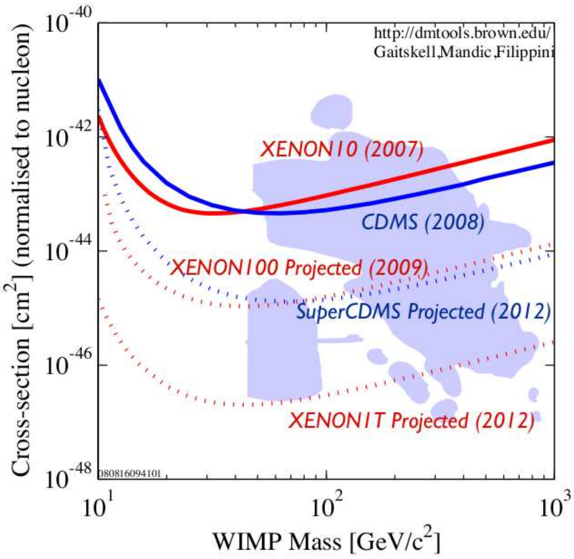

Figure 4: WIMP-nucleon cross-section upper limit (90%C.L.) from direct dark matter search experiments. The projected upper limits are shown as dashed lines.

is enclosed by a teflon structure, made with interlocking panels. Teflon is used as an effective UV light reflector and as an electrical insulator. The TPC is equipped with four wire meshes, two in the liquid and two in the gas. The bottom mesh serves as cathode and the next one positioned just below the liquid level, together with a series of field shaping rings, form the 30 cm drift region. The top two meshes, together with the one below the liquid level, serve to define the gas proportional scintillation region. The wire meshes and top PMT array are mounted in an SS cylinder closed on top, but open at the bottom. The cylinder works like a “diving bell”, keeping the liquid level at a precise height. A positive pressure in the bell is provided by the gas returning from the continuous recirculation system. The “diving bell” system was developed and used to control the liquid level in the XENON10 detector.

A Pulse Tube Refrigerator (PTR) with 170 W cooling power will be used to liquefy and keep the liquid temperature. As demonstrated with XENON10, the PTR provides excellent long time stability of operation, with temperature deviations not exceeding 0.1^{o}C and pressure changes less than 1%. The key difference is that the cryogenic system which was previously mounted on top of the XENON10 cryostat, inside the Pb/Poly shield enclosure, is now moved outside the shield, to minimize background.

An un-vetoed event in the XENON100 TPC will be of interest if it features only two pulses: one from the direct scintillation light in the liquid (S1, with a characteristic width >100 ns) and one from the ionization charge, amplified via scintillation

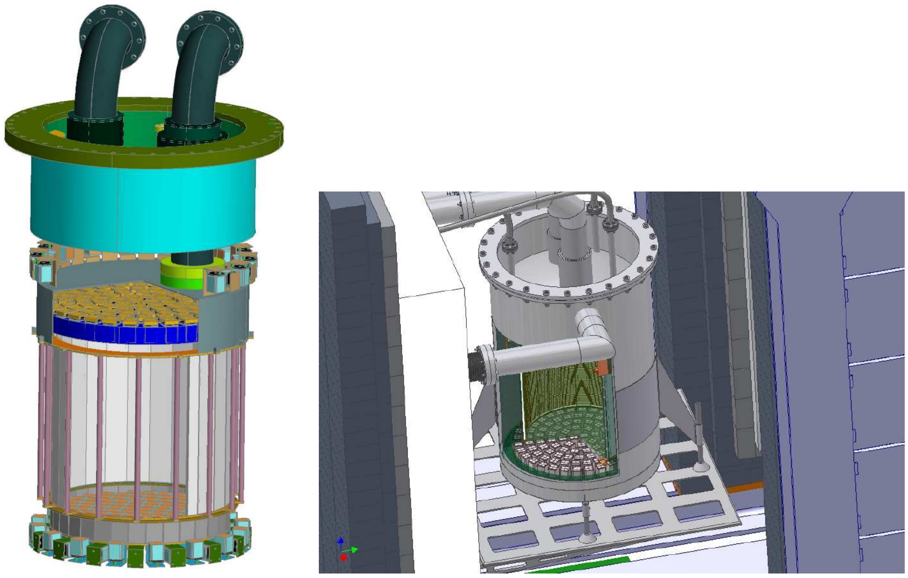

Figure 5: Schematic of the XENON100 TPC (left) and the cryostat inside the shield (right).

in the gas (S2, with characteristic a width of a few μs). The two pulses occur within the maximum drift time of 150 μs, for a saturated drift velocity of 2 mm/μs in LXe.

The greatest challenge for the readout electronics is the large dynamic range required: the system must be able to handle signals ranging from single photoelectrons (scintillation signals in the keV range) up to large S2 pulses from gamma ionization signals (up to thousands of photoelectrons). Moreover, the time difference between S1 and S2 pulses must be measured with sub-μs resolution in a 300 μs range, to provide 3-D position reconstruction throughout the drift volume (we require twice the maximum drift time, to enable triggering either on the S1 or S2 pulse). We have adopted a DAQ design based on CAEN 1724 Flash ADCs, with a sampling rate of 100 MHz. To reduce the large data rate, zero-suppression is implemented with the FPGA (field programmable gate array) available on each board.

High purity liquid xenon is an essential requirement for a TPC like XENON100, with a drift gap of 30 cm. The purity must be preserved at all time during the detector operation in order to ensure stable performance. With XENON10 we have fulfilled this requirement by continuous gas circulation through a high temperature getter, reaching an electron lifetime of (1.8 ± 0.4) ms. While more challenging, we expect to achieve similar purity level in XENON100. Similarly demanding, is the requirement for very low level contamination of radioactive ^{85}Kr in Xe. By using a dedicated cryogenic distillation column, we will reduce the ^{85}Kr concentration well below the 50 ppt (part per trillion) required by the XENON100 sensitivity goal.

4 Summary

The nature of dark matter remains a fundamental mystery, which likely involves new particles and new physics beyond the standard model. In direct detection experiments one searches for the nuclear recoils resulting from the rare collisions of dark matter particles with the nuclei in the detector's target. For the XENON experiment the target is liquid xenon and the detector is a two-phase TPC, capable to measure simultaneously the ionization and the scintillation signals produced by nuclear recoils, in competition with the much larger number of electron recoils resulting from background radiation. The XENON collaboration has completed the commissioning of the XENON100 TPC, which has replaced the XENON10 prototype in the same shield and location at the Gran Sasso Underground Laboratory (LNGS). With a raw exposure of 6000 kg-days, free of background, XENON100 will be able to reach $\sigma \sim 2\times10^{-45}$ cm^2 at 100 GeV, by the end of 2009. A further reduction in background and an increase in fiducial mass, will enable another order of magnitude improvement in sensitivity by 2012. The next phase will be a detector at the ton scale (XENON1T) with a sensitivity goal at the $\sigma \sim 10^{-47}$ cm^2 level for the spin-independent WIMP-nucleon cross section, more than 3 orders of magnitude better than the current best limits from XENON10 [10] and CDMS [7].

5 Acknowledgements

My work on the XENON Dark Matter Project is supported by the National Science Foundation with Award No. PHY-0705337 to the Columbia Astrophysics Laboratory.

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