Direct Detection of Dark Matter with MiniCLEAN

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Abstract. Overwhelming astrophysical evidence indicates that non-baryonic Dark Matter constitutes most of the mass of the Universe. Nevertheless, the particle nature of Dark Matter remains a long standing mystery. The use of noble liquids as scintillators in single and dual-phase detectors are some of the most promising scalable WIMP detectors currently planned and under construction. The MiniCLEAN experiment will have 92 photomultiplier tubes (PMTs) looking at a liquid Argon detector mass of over 500 kg in a single-phase configuration. It will use Pulse Shape Discrimination (PSD) techniques to search for low-energy WIMP nuclear recoils inside a fiducial volume. Liquid Argon would be interchangeable with liquid Neon to study $A^2$ dependence of a potential signal and examine backgrounds external to the cryogenic liquid. For the Argon run, MiniCLEAN projects a sensitivity in terms of spin-independent WIMP-nucleon cross-section of $2 \times 10^{-45}$ cm$^2$ for a mass of 100 GeV/$c^2$. A status report of MiniCLEAN will be presented as well as plans to deploy the experiment at SNOLAB.

1. Introduction

It has been well established by cosmological observations [1] that the Universe is made of $\sim 85\%$ non-baryonic and non-luminous matter, called dark matter that had non-relativistic speeds at the time of structure formation. The nature of dark matter remains one of the biggest challenges in Astroparticle physics today. Extensions of the Standard Model of particle physics propose a variety of dark matter particle candidates. Among the well motivated candidates are the Weakly Interacting Massive particles (WIMPs) [2, 3, 4, 5]. Using standard assumptions of the WIMP halo that is gravitationally bound to the Milky Way we expect a mean nuclear recoil energy due to WIMP coherent scattering at a scale of tens of keV [6, 7]. The rate is currently limited by observation of less than 0.1 event/kg/day [8, 9] above $\sim 40$ GeV/$c^2$ WIMP mass. Recently, the DAMA/LIBRA collaboration has reported 1.17 ton-years of data from which an annual modulation with the correct phase was observed with a significance of 8.9$\sigma$ [10]. When the DAMA/LIBRA modulation is confronted with the null observation of other direct detection experiments, light WIMPs have been invoked, if this modulation is indeed a signal due to dark matter [11].

The use of liquid noble elements as scintillators for direct detection of dark matter in single and dual phase configurations are one of the most promising techniques to reach sensitivities beyond $10^{-44}$ cm$^2$ in WIMP-nucleon spin-independent cross section. Particularly bright are the efforts by the WARP [12], LUX [13], XENON10/100 [9, 14] and ZEPLIN III [16] collaborations. The status of the MiniCLEAN experiment, a single phase liquid Argon and Neon detector, will be presented.
2. Experimental technique

The use of liquid noble gases as targets in direct detection experiments has bloomed in the last ten years due to their bright scintillation when exposed to radiation (40 photons per keV in Argon [15]), the ion mobilities, their high-Z for self-shielding purposes and the ability to purify the liquid with well established methods such as charcoal traps and getter technologies. The nuclear recoil discrimination is obtained either with timing of the scintillation light alone (single-phase experiments) or from the ratio of the produced scintillation to ionization (dual-phase experiments).

Natural argon being cheap and readily available (∼ $5 per kg) has $^{39}$Ar, a $\beta$-emitter produced by cosmic-rays and with an activity of 1 Bq/kg and a half-life of 269 years. Events from the $\beta$-decays of $^{39}$Ar produce $\sim 10^7$ electronic recoils/keV/year/100 kg of liquid Argon, therefore the need for high-efficiency discrimination method. Neon on the other hand, does not have any long-lived radioactive isotopes and would not require such high-efficiency discrimination methods to search for dark matter. Nevertheless, due to the $A^2$ enhancement of the spin-independent WIMP-nucleon cross section, Argon has the advantage over Neon on event rate although with a higher threshold.

Dual-phase Argon detectors using natural Argon are limited in size due to pile-up events from $^{39}$Ar (500 kg to 1 ton). Recently, a sample of underground Argon has been shown to have less than 0.4 Bq/kg $^{39}$Ar [17]. Large quantities of depleted Argon make ton-scale Argon TPCs viable for dark matter searches and extend the sensitivity of single-phase experiments by allowing to lower the threshold.

The MiniCLEAN experiment aims at using a single-phase configuration with over 500 kg of liquid Argon and use pulse shape discrimination methods as well as position reconstruction to look for WIMP scatters inside a fiducial volume. The liquid Argon target would be interchangeable with liquid Neon to examine any potential signal and external backgrounds taking advantage of the $A^2$ dependance.

When ionizing radiation interacts in any liquid noble gas, two types of dimer molecules are formed: singlet and triplet states. The singlet states quickly decay into two ground state atoms but, due to a forbidden spin flip, the triplet state survives a few microseconds more compared to the singlet in liquid Argon and Neon. The peak wavelength of the emitted photons as the singlet and triplet states decay is 129 nm and 80 nm for Ar and Ne respectively, and therefore the need to use scintillation-grade tetraphenyl-butadiene (TPB) wavelength shifter as means to convert the VUV light to the visible where it can be readily transported through light-guides and detected using PMTs. The fraction of light arriving in the first 90 ns as compared to the total amount of light is the parameter used for Pulse Shape Discrimination (PSD) in both liquid Argon and Neon [18, 19].

Eventually, a large multi-ton Neon detector would be sensitive to $pp$ neutrinos as well as dark matter, in which case the main background to dark matter is the $pp$ solar spectrum itself [19].

3. Calibration across the detector target

For the same reason that liquid noble gas based detectors use self shielding, calibrations with sources placed outside the detector or point sources inside of it make it difficult to have a uniform energy calibration throughout the detector target. Furthermore given the energy scale of nuclear recoils expected from WIMPs and that of the $pp$ neutrino flux, an energy line at these scales, preferably at or close to the threshold is needed. A low-energy radioactive source ($^{83}$Kr$m$) that can be diffused through the target volume and at the same time have decay energies at tens of keV was developed and tested in a 4 kg liquid Argon chamber. $^{83}$Kr$m$ was produced in the decay of $^{83}$Rb, with a half-life of 86.2 days (see Figure 3 upper left schematic for the decay chain of $^{83}$Rb). The half life of $^{83}$Kr$m$ is 1.83±0.02 hrs through two electromagnetic decays (emission of a conversion electron accompanied by either an x-ray or another electron) with
Figure 1. Upper left: Decay diagram of $^{83}$Rb showing the energy levels in keV. There is a 75% probability that $^{83}$Rb decays into $^{83}$Kr$^{m}$ which then decays to the 32.1 and 9.4 keV electromagnetic transitions. Lower left: An example of a $^{83}$Kr$^{m}$ event that shows the 32.1 and 9.4 keV electromagnetic transitions. Upper right: The energy spectrum as observed in Argon for the $^{83}$Kr$^{m}$ run in which the sum of the electromagnetic transitions gives precisely a 41.5 keV peak with 8.2% ($\sigma/E$) and 6.0 pe/keV light yield. Lower right: The $^{83}$Kr$^{m}$ run in Neon. A light yield of 3.0±0.3 pe/keV was observed and a 19% resolution at the 41.5 keV peak [21].

energy 32.1 keV and 9.4 keV. $^{83}$Kr$^{m}$ has been used before as a diagnostic tool in the study of beta decay of tritium [20]. On liquid Argon, after performing a background subtraction and fitting the resulting peak to a gaussian, an energy resolution of 8% ($\sigma/E$) is measured at 41.5 keV and 19% for the liquid Argon and liquid Neon run respectively. Due to the timing characteristics of Argon, it is not possible to separate the light generated by the 9.4 keV decay to that of the late component of the 32.1 keV transition (see Figure 3) [21].

4. The nuclear recoil scintillation efficiency
The energy threshold of the MiniCLEAN experiment is determined by the PSD in combination with the nuclear recoil scintillation efficiency $L_{eff}$. A recent measurement of $L_{eff}$ was made using a D-D generator that produces neutrons that in turn scattered off a 4 kg liquid Argon target inside a cryostat and from here into an organic liquid scintillator that was used as a coincidence trigger. By changing the orientation of the organic scintillator with respect to the trajectory from the neutron source to the liquid Argon target, a sampling of the scattering angles was made and from this an extraction of the nuclear recoil energy in the liquid Argon target nucleus. At every given angle, the electron-equivalent energy as well as the nuclear recoil energy (keV$_r$) was measured. The ratio of nuclear recoil scintillation response to the electronic
recoil response was measured to be \(0.25 \pm 0.02 + 0.01\) (correlated) for nuclear recoils between 10 to 250 \(\text{keV}_r\) \cite{22}. A previous measurement of the nuclear recoil scintillation efficiency in liquid Argon was made by the WARP collaboration of \(0.28 \pm 10\%\) at 65 \(\text{keV}_r\) \cite{12}.

5. Measurement of LAr pulse shape discrimination

The DEAP-1 experiment is a 7 kg Argon stainless steel chamber with 6-inch diameter glass windows mounted on the sides and viewed by two 5-inch PMTs each coupled to a light guide 8-inch long and operated at room temperature. The purpose of DEAP-1 is to study the PSD in liquid Argon and to understand backgrounds such as Radon. The inner surfaces of the windows as well as an inserted acrylic sleeve coated with TiO\(_2\) are coated with TPB. The outer vacuum chamber is made of PMMA acrylic and has a 12-inch diameter. Further details on the experimental setup can be found in Boulay et al. \cite{23}.

The electron equivalent energy calibration of DEAP-1 was made using a 10 \(\mu\)Ci encapsulated \(^{22}\)Na source located outside the Argon chamber. The \(^{22}\)Na source emits a 1.2 MeV \(\gamma\)-ray as well as a positron that in turn annihilates in the source container into back-to-back 511 \(\text{keV}\) \(\gamma\)-rays. In order to reduce accidental backgrounds, a NaI detector in annular shape as well as another NaI detector as one of the caps of the annular detector is used. Therefore, events with a 511 \(\text{keV}\) \(\gamma\)-ray scatters in Argon, with the two additional detectors tagging the other 511 \(\text{keV}\) and the 1.2 \(\text{MeV}\) \(\gamma\)-rays with the source being placed on the axis of the annular NaI detector. The measured light yield was \(2.8 \pm 0.1\) photoelectrons/\(\text{keV}_{ee}\).

![Figure 2. Left: \(F_{\text{prompt}}\) as a function of photoelectrons as measured by the DEAP-1 prototype when shinned with an Am-Be source. Events in the upper band (0.7 < \(F_{\text{prompt}}\) < 1.0) are mostly nuclear recoils. Right: \(F_{\text{prompt}}\) histogram of 16.7 million electronic recoil events with 120-240 photoelectrons from the \(^{22}\)Na calibration source (blue) and 100 nuclear recoils from the Am-Be neutron source (red) as measured by DEAP-1 \cite{23}.](image-url)

Data taken with an Americium-Beryllium (Am-Be) calibration source is shown on the left plot of Figure 5. Nuclear recoil events show high-\(F_{\text{prompt}}\) (0.7-1.0) while \(\gamma\) and \(\beta\)-rays appear in the \(F_{\text{prompt}}\) band below it. Where \(F_{\text{prompt}}\) is defined as

\[
F_{\text{prompt}} = \frac{Q_{\text{prompt}}^A + Q_{\text{prompt}}^B}{\text{Total PE}}
\]

where \(Q_{\text{prompt}}^A, B\) is the charge measured 50 ns before the leading edge of the pulse and until 150 ns after the leading edge of PMT A or B. Total PE refers to the total number of photoelectrons.
The right plot on Figure 5 shows the $F_{\text{prompt}}$ distribution for $\gamma$-rays and nuclear recoils between 120-240 photoelectrons. From this data, Boulay et al. found no misidentification of the 16.7 million $\gamma$-rays. Furthermore, with a neutron efficiency of 50% between 70-240 photoelectrons ($\sim$ 25-86 keV$_{ee}$) the measured misidentification ratio between $\gamma$-rays and nuclear recoils was measured to be $1 \times 4.7 \times 10^{-8}$.

![Figure 3.](image)

**Figure 3.** Upper-left: Schematic drawing of the MiniCLEAN water tank as well as the outer and inner vessel. Upper-right: Cross section drawing of the outer vessel and inner vessel showing the “optical cassettes”. Lower-left: SNOLAB Cube Hall, house of the DEAP-3600 and MiniCLEAN experiments showing the finished deck. Lower-right: Picture of the finished outer vessel.

6. MiniCLEAN engineering

The MiniCLEAN detector will have 92 PMTs (Hamamatsu R5912-02MOD tubes [24]) immersed in liquid Argon and will have over $\sim$500 kg of active target. Each of the PMTs will be assembled in “optical cassettes”. An optical cassette is made of a PMT, the light guide and a thin acrylic window. In order to detect the VUV light form Argon and Neon, the light will be converted to the blue spectrum by using a layer of TPB wavelength shifter. The 92 optical cassettes will be cleaned and assembled inside a glove box under radon-free (or mitigated) environment to minimize the contact of the surfaces with radon daughters. After full assembly of the cassettes under vacuum, the PMTs will be submerged in liquid Argon (or Neon) and the liquid will be constantly recirculated in order to be purified. The purification system will be a conversion to the gas phase in order to feed it into a getter and charcoal trap. The optical cassettes are being designed and prototyped at Los Alamos National Laboratory using a custom made cryostat that can hold pressurized liquid Argon to 3 atmospheres. These tests will study the light collection by the light guide, the reflectivity of the aluminum coating and the efficiency of the PMT. This data will be used to benchmark the Monte Carlo simulation as well.
External to the outer vessel, MiniCLEAN will have a water shield ~5.6 m in diameter and ~7.8 m in height. The water tank will be instrumented with PMTs and its primary purpose will be to serve as a muon veto. In Figure 5 it is shown, in the upper-left a drawing of the MiniCLEAN water tank as well as outer and inner vessels. In the upper-right a cross-section of the outer vessel and inner vessels with the optical cassettes is shown. The lower-left and lower-right pictures show the location at SNOLAB of the MiniCLEAN experiment and the finished outer vessel respectively.

7. Projected sensitivity

In order to achieve a sensitivity of the order $10^{-45}$ cm$^2$ in terms of spin-independent WIMP-nucleon cross section, MiniCLEAN plans to run for two years in liquid Argon mode. In order to achieve zero-background at this level, MiniCLEAN will mainly have to discriminate the $^{39}$Ar $\beta$-rays, shield or tag fast neutrons from ($\alpha$, n) reactions in the PMT glass and reduce backgrounds associated with radon daughters at the level of $1 \alpha/m^2$/day on the acrylic.

In Figure 7 it is shown the projected sensitivity reach of MiniCLEAN assuming a zero-background experiment and that of various other competitive experiments using other targets and techniques [21]. The sensitivity of MiniCLEAN assumes a light yield of 7.0 pe/keV and a threshold of 44 keV$_r$. For DEAP-3600 and MiniCLEAN, a time period of 2 years of exposure is assumed. The commissioning of MiniCLEAN is scheduled for spring 2011. The outer vessel has been completed and the inner vessel is being fabricated, MiniCLEAN is expected to be taking data in Fall 2011.

**Figure 4.** The projected sensitivities with respect to spin-independent WIMP-nucleon cross section in MiniCLEAN and DEAP-3600 [6, 21, 28] together with that of competitive experiments, SuperCDMS, XENON 100 and LUX. Model predictions are shown in the colored patches. The shaded pink and yellow patches correspond to allowed parameter space in model predictions for a SUSY WIMP [25, 26]. The light blue patch is the allowed parameter space for a KK WIMP dark matter [27].

| WIMP Mass (GeV/c^2) | SI WIMP-nucleon Cross Section (cm^2) |
|---------------------|--------------------------------------|
| $10^{42}$           | $10^{-42}$                            |
| $10^{43}$           | $10^{-43}$                            |
| $10^{44}$           | $10^{-44}$                            |
| $10^{45}$           | $10^{-45}$                            |
| $10^{46}$           | $10^{-46}$                            |
| $10^{47}$           | $10^{-47}$                            |

WIMP Mass (GeV/c^2) | SI WIMP-nucleon Cross Section (cm^2) | XENON100 (2010) | CDMS (2010) | XENON100 (2011) | MiniCLEAN | LUX | CLEAN, natural Ar | CLEAN, depleted Ar | CLEAN, Ne
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