ArDM: a ton-scale liquid Argon experiment for direct detection of Dark Matter in the Universe

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Abstract. The ArDM project aims at developing and operating large noble liquid detectors to search for direct evidence of Weakly Interacting Massive Particle (WIMP) as Dark Matter in the Universe. The initial goal is to design, assemble and operate a \( \approx 1 \) ton liquid Argon prototype to demonstrate the feasibility of a ton-scale experiment with the required performance to efficiently detect and sufficiently discriminate backgrounds for a successful WIMP detection. Our design addresses the possibility to detect independently ionization and scintillation signals. In this paper, we describe this goal and the conceptual design of the detector.

1. Introduction
Astronomical observations give strong evidence for the existence of non-luminous and non-baryonic matter, presumably composed of a new type of elementary particle. A leading candidate is the Weakly Interacting Massive Particle (WIMP). If they exist, they should form a cold thermal relic gas which can be detected via elastic collisions with nuclei of ordinary matter. The detection of these WIMPs is based on the capability of measuring the recoils of target nuclei with kinetic energy in the range of 10 – 100 keV. The signal is therefore quite elusive and it is a rare event given the weak coupling. Furthermore the rate is not easily predicted, since it depends on many poorly defined variables, even in the context of well defined extensions of the SM like e.g. SUSY [1]. Nonetheless, ton-scale targets are nowadays to be contemplated in order study with high statistical power the DAMA result [2] or alternatively to cover large fractions of the remaining theoretical parameter space.

Within the ICARUS R&D program, it was first shown that noble liquid detectors using Xenon or Argon could act as targets for WIMP detection [3, 4]. Xenon or Argon provide a high event rate because of their high density and high atomic number and large target masses are readily conceivable. They have high scintillation and ionization yields because of their low ionization potentials. Both scintillation and ionization are measurable and can be used to very effectively discriminate between nuclear recoils and gamma/electron backgrounds.

The use of noble liquid gases to detect WIMP dark matter is currently the subject of intense R&D carried out by a number of groups worldwide [5, 6, 7]. In these detectors, one relies on the simultaneous detection of the ionization charge and of the scintillation light produced during a nuclear recoil event. A main subject for any such detector is the method of the readout for the ionization and scintillation. Currently, the XENON [5], ZEPLIN [6] and WARP [7] designs rely exclusively on photomultipliers (PMTs) for their readout. The possibility to directly detect the ionization charge is less well developed although it might provide alternative and potentially
large benefits. Given the low energy thresholds necessary to efficiently detect WIMP signals, this method however requires the charge to be amplified before it is readout. While amplification is not possible in the liquid Argon phase, it can be achieved in the vapor in equilibrium on top of the liquid, although operation in this context precludes the inclusion of common avalanche quenchers, since they will condense in the liquid phase.

In 2004 we have initiated the Argon Dark Matter experiment (ArDM\(^1\), see http://neutrino.ethz.ch/ArDM/). The goal of this project is to design, assemble and operate a bi-phase \(\approx 1\) ton Argon detector with independent ionization and scintillation readout, to demonstrate the feasibility of a noble gas ton-scale experiment with the required performance to efficiently detect and sufficiently discriminate backgrounds for a successful WIMP detection.

2. Conceptual design
The choice of natural Argon for the initial ton-scale target instead of Xenon can be motivated by three arguments:

(1) The detection energy threshold depends on the achievable performance of the light and ionization detection systems. The event rate in Argon is less sensitive to the threshold on the recoil energy than for Xenon because of form factors. For a threshold of \(\approx 30\) keVr, the rates on Xenon and Argon per mass are similar (See Figure 1). With such a threshold a WIMP-nucleon cross-section of \(10^{-44}\) cm\(^2\) yields about one event per ton per day (See Figure 2).

(2) Argon is much cheaper than other noble gases, and we have acquired sizeable experience in the handling of massive liquid Argon detectors within the ICARUS program. A ton-scale Argon detector is hence readily conceivable, safe and economically affordable.

(3) The scientific relevance of obtaining data on Argon and Xenon is given by the fact that recoil spectra in Xenon and Argon are different (due to kinematics), providing an important crosscheck in case of a positive signal.

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Figure 1. Event rate per ton per day on Argon and Xenon targets for winter and summer periods as a function of detection threshold for a WIMP-nucleon cross-section of \(10^{-42}\) cm\(^2\) = \(10^{-6}\) pb and a WIMP mass of 100 GeV.

Figure 2. Cross-section normalized to nucleon versus WIMP mass. The expected event rates for a true recoil energy threshold of 30 keVr are indicated by horizontal thick lines. With such a threshold a WIMP-nucleon cross-section of \(10^{-44}\) cm\(^2\) yields one event per ton per day.

One non-negligible drawback of natural Argon liquefied from the atmosphere is the existence of the radioactive isotope \(^{39}\)Ar which is a beta-emitter with a lifetime of 269 years and a value \(Q=565\) keV. Its concentration in atmospheric Argon is well known \(^8\) and will induce a

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\(^1\) ETH Zürich, Granada University, CIEMAT, Soltan Institute Warszawa, Zürich University.
background decay rate of \( \approx 1 \text{ kHz} \) in a 1 ton detector. In principle, the intrinsic electron/nuclear recoil rejection provided by the ratio of the scintillation to the ionization yields, which is extremely high for nuclear recoils (i.e. WIMP events), is sufficient to suppress this background, provided this ratio can be measured precisely. This fact needs to be experimentally further understood since rejection factors exceeding \( > 10^9 \) are needed. We intend to fully address it with our proposed 1 ton prototype, i.e. a detector of the relevant size\(^2\). We are also studying other ways to obtain \(^{39}\)Ar-depleted targets, by using Argon extracted from well gases (extracted from underground natural gas) rather than from the atmosphere. This would provide a reduction of this background although its cost is to be estimated. On the other hand, the \(^{39}\)Ar decays, evenly distributed in the target, provide a precise calibration and monitoring of the detector response as a function of time and position.

The conceptual layout of the detector is shown in Figure 3. More details can be found in Ref. [9]. A main feature is the possibility to independently detect the ionization charge and scintillation light. Following an ionizing event, ionization charges will be drifted towards the top of the detector where they will be extracted from the liquid to the gas phase. There, a Large Electron Multiplier\([10, 11]\) (LEM) system will amplify the electrons in order to produce a detectable signal. By segmenting the LEMs, an image of the event will be obtained, retaining the salient features of the ICARUS imaging technology, although with a much lower energy threshold.

Because background discrimination requires the ratio of the scintillation to the ionization yields, the primary VUV scintillation light of argon (128 nm) will be reflected by specially conceived high reflectivity mirrors made of \( Al – MgF_2 \) coated Mylar foils\([12]\) and located on the field shaping electrodes. The photons are detected via a light readout system located behind the transparent HV cathode. R&D efforts are under way to improve on the light collection efficiency (about 5% with PMTs), and hence on the threshold and background discrimination, by using wavelength shifters and alternative light readout systems such as avalanche photodiodes.

Charge imaging and time correlation between scintillation and charge will provide a precise localization of the event vertex (in space), hence a good fiducial volume definition, important for \( \gamma \)-ray and slow neutrons background rejection from surrounding elements.

The time dependence of scintillation light can be used to further discriminate between heavy recoils and other backgrounds (in addition to primary versus secondary signal).

A second feature of the experiment is the possibility to reach very high drift fields up to 5 kV/cm in order to detect an ionization signal even in the presence of highly quenched nuclear

\(^2\) We note that achieving the required performance on small prototypes is less challenging.
recoils as in the case of a WIMP interaction.

3. Outlook
A natural follow-up of the use of liquid noble gases as media for detectors is the extension of their application to the direct detection of nuclear recoils induced by dark matter. We have presented our plans for the construction of a 1 ton prototype whose goal is to demonstrate the validity of our design. This goal requires a successful implementation and operation of (a) a high drift field device; (b) a LEM based charge readout; (c) a highly efficient Argon scintillation light detection system.

Given the challenging nature of the experiment which requires innovations both at the level of the detection methods and at the level of background rejection, our immediate plan is to fully design and acquire the needed equipments to setup and operate the 1 ton prototype at CERN. The operation of the prototype will involve cryogenic, LAr purification, HV system, drift volume, charge amplification + readout, and light readout. It will allow us to define and set up all the necessary equipment and infrastructure for a safe operation of the detector.

Our first milestone is a proof of principle and stability studies, and further optimization of the design for a highly efficient $\gamma$-ray and beta electron ($^{39}$Ar) rejection vs. nuclear recoils. Strong neutron shielding and stringent requirements on detector radio-purity will be fully addressed in a second phase. Assuming the successful operation of the prototype, we will consider a deep underground operation. With the assumed recoil energy threshold of 30 keVr, a WIMP-nucleon cross-section of $10^{-42}$ cm$^2$ would yield 100 events per day per ton (see Figure 2). The sensitivity expectation of the ArDM 1 ton prototype would therefore be around $\sim 10^{-6}$ pb or better. The discovery region of the ArDM 1 ton detector, assuming that sufficiently low gamma and neutron backgrounds can be reached, would be $\sim 10^{-8}$ pb. Its ultimate sensitivity for a year of operation would be $\sim 10^{-10}$ pb. Scaling linearly with mass, a $\approx 10$ ton detector would reach $<10^{-11}$ pb in a year of operation.

Acknowledgments
The help of all ArDM colleagues from ETH Zürich, Granada University, CIEMAT, Soltan Institute Warszawa, and Zürich University, is greatly acknowledged. Informal contributions from P. Picchi (LNF) are also greatly recognized.

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A memorandum has been sent on September 9th, 2005 to the Canfranc Scientific Committee.