Towards a ton scale LAr WIMP Detector

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ArDM is a prototype for a ton scale liquid argon WIMP-detector designed to record scintillation light and ionisation charge from recoiling nuclei down to a threshold of 30 keV$_r$. The detector uses the dual-phase principle to suppress background by the charge-to-light ratio, the scintillation time structure, and the topology of individual events. Design and developments of the detector components were strongly driven by scalability. The entire assembly is currently commissioned on surface at CERN. This allows for the test of principle functionalities, implementation of missing components, and preparation for the installation in the underground site. The project is briefly reviewed, with emphasis on selected features of the liquid argon technology.

1 Introduction

Prime candidates for the dark matter in our universe are a unknown kind of stable elementary particles which remained as a cold thermal relic from the big bang, so called weakly interacting massive particles (WIMPs). Their coupling strength to normal matter is estimated from their actual (gravitational) abundance and inferred to be situated at the weak scale. Direct detectability via weak neutrino-like couplings were first calculated in the 1980's [1] and predict nuclear recoils in a earth based detector with a decreasing energy spectrum of up to roughly 100 keV$_r$ depending on the (unknown) WIMP mass, target composition and thermal distribution of the WIMPs (halo models). The cross section of WIMPs is equally unknown. Scattering rates in a ton liquid argon detector are estimated from present searches [2] not to exceed a few recoils per day at a threshold of 30 keV$_r$. This has to be confronted with the background rates present in such a kind of detector. An order of 1 kHz of electronic recoils is expected just from the ^{39}Ar content in natural argon from the atmosphere [3]. However, recently it was demonstrated that argon extracted from liquified dwell gases contains substantially less of this radioactive isotope [4]. Liquid argon is particularly well suited for electronic background discrimination due to its large light and charge yields and the large difference in decay times of the fast and slow scintillation components (ionisation density effect [5]). Furthermore in detectors of the size described here background from neutrons imitating WIMP interactions can be estimated by statistical means [6, 7] from background neutron interaction multiplicities and their energy distributions.

The goal of the ArDM project[8] is to design, assemble and operate a dual-phase ton scale liquid argon detector with independent ionisation and scintillation readout, and to demonstrate the required performance. This is achieved in a staged approach with the upcoming installation of the experiment at the Canfranc underground site in the Pyrenees.

2 Experimental overview

A WIMP interaction in liquid argon leading to a 30 keV$_r$ nuclear recoil produces about 300 VUV photons (128 nm), together with a few ionisation charges, the latter number depending strongly on the strength of the electric field [9]. Recoiling electrons in the same energy range produce about 4 times more light [10] and exhibit several hundreds of ionisation charges. Figure 1 shows the conceptual layout of the experiment with free charges drifting to the top of the detector, while the light is wave shifted on the side walls and reflected down to an array of PMTs at the bottom (diffusion cell design[7]). The vertical electric field (up to 3 kV/cm) prevents some electrons from recombination and sweeps them upwards. It is provided by field shaping ring electrodes coupled to a diode-capacitor charge pump system (Greinacher/Cockroft-Walton circuit) which is fully immersed in the liquid argon [11]. Charges drifting to the interface are extracted into the gas by a strong electric field and swept towards a Large Electron Multiplier (LEM, [12]) and a segmented anode for 2D position reconstruction. The 3D image of the event is obtained by the drift time.

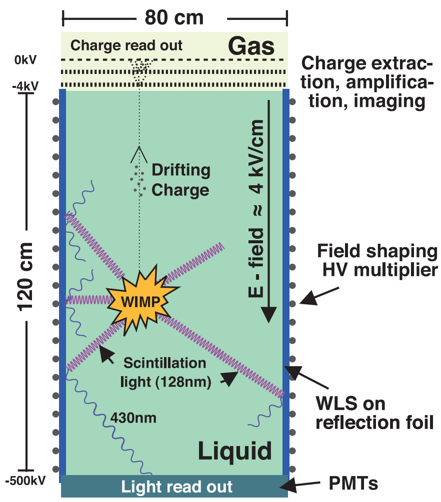

Figure 1: Conceptual design

The 128 nm VUV scintillation light is emitted isotropically from any interaction point in the fiducial volume and converted into blue light (420 nm) by a thin deposit of tetra-phenyl-butadiene (TPB) on Teflon fabric reflector foils (Tetratex). The shifted and reflected light is collected at the bottom of the cryostat by 14 hemispherical 8" photomultiplier tubes immersed in the liquid (Hamamatsu type R5912-02MOD, featuring bialkali photocathodes with Pt underlay). Each PMT is soldered from its leads onto a 3 mm thick printed circuit board providing both the mechanical footing and the voltages for cathode and dynodes by means of passive electronic components. A TPB deposition on the PMT surface is also performed to improve direct VUV light detection. To optimise the performance of the light readout in ArDM, a range of reflectors and TPB deposition combinations were investigated in small setups, where argon scintillation light was generated by radioactive sources in gas at normal temperature and pressure. Detailed descriptions of the developments for the light readout system can be found in [13, 14, 15]. The current choice of main reflectors consists of 254 μm thick Tetratex foils which have nearly 100% diffuse Lambertian reflectance. A coating density of 1 mg/cm^2 of TPB was evaporated onto these foils and 0.05 mg/cm^2 onto the glass windows for the PMTs.

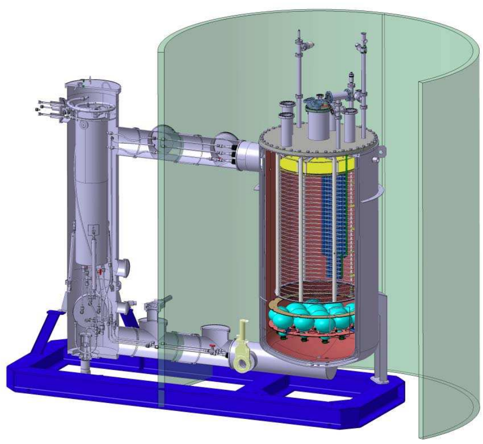

Figure 2: Experimental setup

Presently a 1400 kg (850 kg fiducial) LAr vessel is installed on the surface at CERN. Figure 2 shows the 3D sketch of the main components of this setup. The liquid argon in the fiducial volume (right dewar) is conditioned by a cryogenic purification system (left dewar) separated from the detector to allow for insertion of a neutron shield (indicated by the open cylinder).

So far two test runs were performed, one in single-phase light collection mode and very recently also a second one in double-phase mode with charge extraction and collection on a prototype anode. The surface operation is needed to systematically test all functionalities, complete and upgrade subcomponents and prepare the whole experiment for its final installation in an underground location where physics runs under low cosmogenic background conditions can be performed. Some results and conclusions from the first test run are briefly discussed in the following chapter, while data from the double-phase operation is still under analysis.

3 Recent achievements

A first four weeks engineering run with liquid argon took place in May 2009 dedicated to explore the operational parameters of the system and to test a preliminary light readout setup of 7 PMTs. The run was preceded by a careful assessment of the requirements of the cryogenic system and the related safety issues. A first brief review on results can be found in [20] and a more comprehensive review in [21].

A main point of interest was at first the cleanliness of the setup. Despite a not yet operative recirculation system, good and stable purity of the liquid argon was observed in terms of scintillation yields. From the measured life time τ_2=1.54 μs of the slow scintillation component (triplet excimer states [1]), an upper limit for N_2 and O_2 impurities of 0.1 ppm was estimated (see [22, 23] for details). Hence we found the detector satisfactorily tight and clean.

Further important point of study was the light readout system in respect to yield and energy threshold. As mentioned above only 7 out of 14 Hamamatsu cryogenic PMTs were installed in this first evaluation run. No problems were found in operating the devices at liquid argon temperature. All dark count rates were in the expected ranges (< 10 kHz). Gain fluctuations over the four weeks of cryogenic operation were smaller than 15% and seemed to be correlated on all 7 devices. The exact source could not be identified but probably was due to small temperature or pressure fluctuations. The gain of each PMT is monitored offline from single photons in the event tails and corrected for in the data. The light yield was determined by measuring the response of the detector to photons from radioactive line sources (e.g. ^{22}Na). For this purpose source spectra recorded at different heights were compared to the corresponding spectra from GEANT4 Monte Carlo simulations. Considerable effort was put in the buildup of a modular software framework for data reconstruction and these simulation (all based on C++). Finally using only a handful of common parameters the MC spectra were describing the measured spectra in all regions better than 10% (see [21] for details).

Wave shifting efficiency (≈ 100%), the diffuse reflection coefficient (95%) and the quantum efficiency of the PMTs (18.5 - 22%) were all consistent with values found during the development of the light readout components [14, 15]. A final light yield of just under 1 p.e./keV$_{ee}$ was estimated for the detector with no electric field, a complete set of PMTs and the LEM installed. Since the light yield for nuclear recoils is lower due to quenching, typically 25% that for electrons in the few 10 keV range [10], we expect from these measurements to detect 30 keV$_r$ nuclear recoils with an average signal of 6 photoelectrons and a resolution of about 40%. For completeness, the energy distribution for events passing trigger conditions of at least two coincident photoelectrons within 10 ns shows that reconstructing events down to a few 10th of keV is feasible.

[1] The literature value for the life time of the triplet excimer state in liquid argon is ≈1.6μs

4 Scintillation light R&D in liquid argon

The interaction of particles with liquid argon is governed by a complex interplay of collisions, excitation and ionisation of argon atoms, recombination of charges and ions, as well as the formation of molecular states (excimers) with possible collisions among the participating partners at different stages in the temporal evolution of the interactions. The yields for the final observables, scintillation light and ionisation charge, are not known very precisely for low energy nuclear recoils and are difficult to determine. For this reason we investigate these numbers and their statistical behaviour by means of a monochromatic neutron source at a small liquid argon cell in one of our laboratories at CERN [16]. This research project also contains the development of methods for data reconstruction and Monte Carlo simulations. The project forms part of the development program of the european consortium DARWIN, a design study for a next generation multiton liquid Xe and Ar facility [17].

As an example fig. 3 shows the effect of different ionisation densities (pulse shapes) from data taken in a small liquid argon cell in the laboratory with different radioactive sources. Two characteristic bands of high and low ionisation density events can be identified as nuclear and electronic recoil bands [2]. Shown is the fraction of the prompt ($\leq$50 ns) to the total light for interactions created by scattered neutrons or alpha particles in the upper branch and scattered photons or muons in the lower branch respectively (pulse shape separator). Using a likelihood based discrimination method a minimum value of about 10^3 was achieved to suppress electronic recoil events from the nuclear recoil band for E_r>30 keV$_r$ in a test chamber in the laboratory [18, 19]. Our task is to optimise these methods for the case of a large liquid argon target as is the case for ArDM.

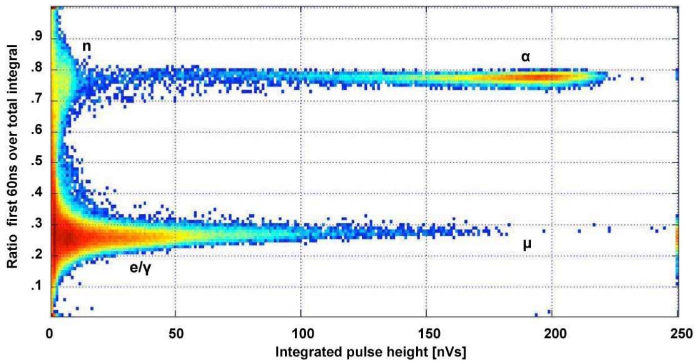

Figure 3: Pulse shape variable versus light yield in LAr

5 Outlook

Further work will be performed to complete the detector with the final charge readout and another test run on the surface is planned for the upcoming months. However many parameters to be tested now require low background environmental conditions and will be carried out after installation in the underground location.

Acknowledgements

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[2]apparently α-particles exhibit the same pulse shape as nuclear recoils (under study)

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