# 1 Search for dark matter with liquid argon

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(ArDM Collaboration)

Weakly Interacting Massive Particles (WIMPs) are prime candidates for the dark matter in the universe (1). Because dark matter has survived since the birth of the universe it has to be stable and only weakly interacting. The lightest supersymmetric particle in SUSY models conserving $R$-parity is the most popular candidate for WIMPs. This is the spin 1/2 neutralino $\chi$ with mass in the 10 GeV to 10 TeV range. $R$-parity conservation ensures that the $\chi$ is stable. Also, the $\chi$ cannot transform into other SUSY particles when interacting with matter, due to its low mass. At the LHC the $\chi$ will therefore manifest itself by a large missing energy. On the other hand, the $\chi$ can scatter e.g. on constituent quarks in nucleons or nuclei (Fig. 1.1), leading to nuclear recoils in the range of 1 – 100 keV. Non-accelerator laboratory search experiments such as ArDM are all based on the detection of such nuclear recoils.

The XENON-10 (2) and CDMS (3) experiments have produced the best upper limits so far of about $4 \times 10^{-8}$ pb for the WIMP cross section on nucleons around WIMP masses of 30, resp. 70 GeV. We plan to improve on the sensitivity reached for WIMPs by 1– 2 orders of magnitude and are constructing at CERN a 1 t liquid argon detector using the two-phase technique to detect both charge and luminescence produced by the recoil nuclei following a WIMP interaction. Our experiment differs from other projects (e.g. (4)) by its large size and its measurement techniques. The Zurich group is studying ways to efficiently collect and detect the VUV light to reach a detection threshold of 30 keV in argon and to suppress background from neutrons and electrons, in particular from the $\beta$-emitter $^{39}$Ar isotope.

Charged particles lead to ionization and excitation of argon atoms forming excimers ($Ar_2^+$ and $Ar_2^*$) with the lowest singlet and the triplet excited states decaying into the ground state (two independent atoms) by VUV photon emission in a narrow band around 128 nm. Reabsorption by argon atoms is energetically suppressed. In liquid the singlet and triplet

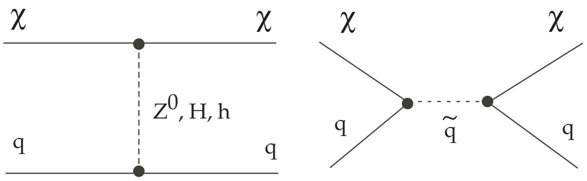

**Figure 1.1: Feynman graphs of $\chi$ interactions with quarks in the nucleon.**

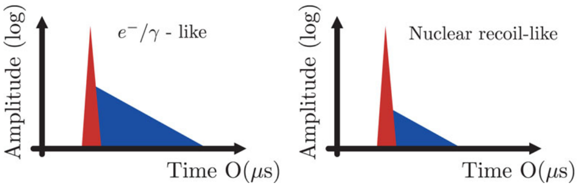

**Figure 1.2: Scintillation time distribution in pure argon for minimum ionizing particles (left) and nuclear recoils (right).**

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states have decay times $\tau_1 \simeq 7$ ns and $\tau_2 \simeq 1.6$ $\mu$s, respectively (5). However, impurities such as water, air and $CO_2$ can absorb VUV light and reduce $\tau_2$ (6; 7; 8). The population ratio singlet/triplet depends on ionization density (Fig. 1.2). For minimum ionizing projectiles such as $e$ and $\gamma$ the ratio is $\approx 1/2$, while for $\alpha$'s and nuclear recoils one finds a ratio of 4 – 5. Hence nuclear recoils from WIMPs populate mostly the fast decaying singlet state.

In addition, the ratio of scintillation to ionization yield is much higher for nuclear than for minimum ionizing particles. This is due to quick recombination which decreases the charge and enhances the luminescence. The higher ratio of light to charge production for nuclear recoils and the higher population of the fast decaying state can both be used to reduce background in WIMP searches.

A sketch of the ArDM detector, as it is now installed in building 182 at CERN, is shown in Fig. 1.3. The working principle is as follows: in liquid argon a WIMP collision leading to 30 keV nuclear recoils produces about 400 VUV (128 nm) photons, together with a few free electrons. The latter are drifted in a strong vertical electric field and are detected in the gas phase by a large electron multiplier (LEM) above the surface of the liquid, while the VUV scintillation light from argon is shifted into blue light by a wavelength shifter (WLS) and detected by cryogenic photomultipliers at the bottom of the vessel. Fifteen Tetratex sheets (120 × 25 cm$^2$) are coated with WLS to cover the cylindrical walls inside the electric field shaping rings. The light detection system consists of fourteen 8″ hemispherical photomultipliers (PMT, Hamamatsu R5912-MOD manufactured with Pt-underlays) at the bottom of the vessel. The PMT glass was coated with a thin WLS layer of a transparent tetraphenylbutadiene (TPB)-paraloid compound to increase the VUV light yield. The cryostat, the purification system, the Greinacher providing the 400 kV HV and the LEM are under the responsibility of ETHZ. Figure 1.4 shows the detector inside the vessel. More details can be found in previous annual reports and in ref. (9).

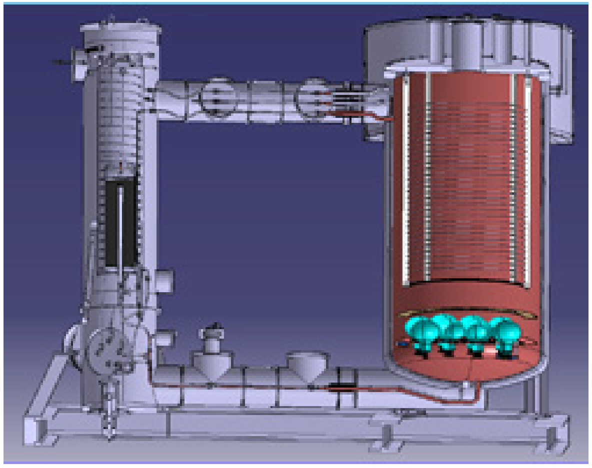

**Figure 1.3: Sketch of the ArDM detector and its purification system on the left.**

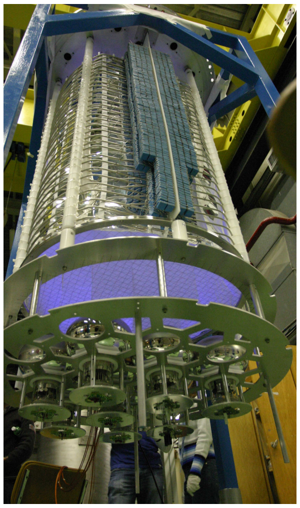

**Figure 1.4: Photograph of the detector showing the Greinacher HV divider, the WLS foils and the photomultiplier support mechanics.**

In parallel to the construction of ArDM we continued R&D activities in our laboratory at CERN to measure and optimize the light output and collection efficiency for charged particles and neutron background (10). Our aim is to achieve a detection efficiency of a few % (defined as the ratio of detected photoelectrons to emitted UV-photons) for the 128 nm fluorescence VUV-light generated in argon. An encouraging $\simeq$ 3% in a test chamber

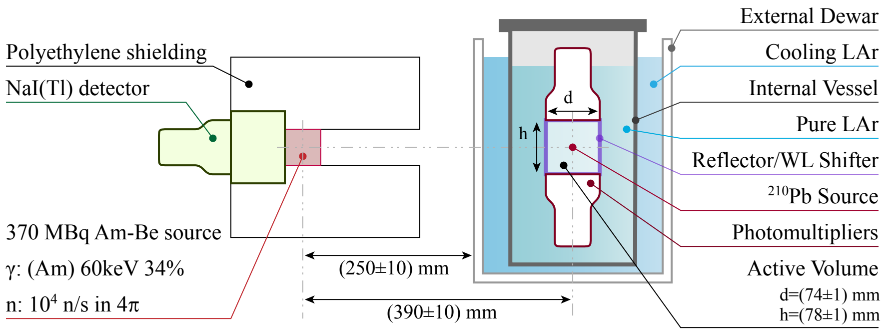

**Figure 1.5:**
**Test cell to measure the light yield from various particles such as neutrons.**

with similar geometry as the 1 t detector was achieved so far.

The setup (Fig. 1.5) is composed of two photomultipliers (Hamamatsu low temperature photomultipliers R6091-02MOD) facing an aluminum cylinder (height = 78 mm, diameter = 74 mm) containing liquid argon (Fig. 1.5, right). A wavelength shifter (1mg/cm$^2$ of TPB [11]) was evaporated on the side reflectors. This time we chose Tyvek from DuPont as substrate for the wavelength shifter to allow a better mechanical stability than the Tetratex used before. The cell was softly baked and pumped for two weeks to reach a pressure of $5 \cdot 10^{-7}$ mbar.

A $^{210}$Pb radioactive source was held on a metal stick in the middle of the active volume. Measurements with neutrons were obtained by placing a 370 MBq Am-Be source next to the experimental setup (Fig. 1.5). The 5.4 MeV $\alpha$'s from americium are absorbed by beryllium producing 2 – 12 MeV neutrons (through the reaction $^9$Be($\alpha$, n)$^{12}$C), 4.4 MeV $\gamma$'s from the atomic level transition $^{12}$C* $\rightarrow$$^{12}$C, and 60 keV photons from $^{241}$Am decays. The source produced about $2{\cdot}10^4$ n/s. It was contained in a high density polyethylene shielding block with two apertures, one for the neutrons, the second for the $\gamma$'s to be detected in coincidence in a NaI(Tl) detector. The neutron flux at the target position was around 30 s$^{-1}$.

As pointed out before, heavily ionizing particles populate mostly the fast decaying singlet states. We therefore define the fraction $r$ of fast ($<$ 50 ns) component to enhance nuclear recoils. The signal from recoil nuclei associated with neutrons is shown in Fig. 1.6

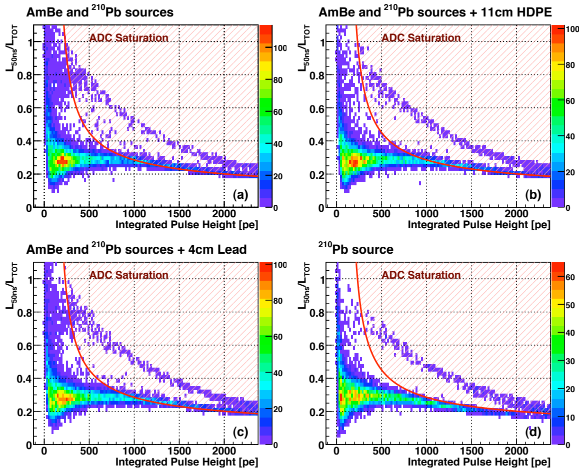

**Figure 1.6: Ratio $r = L_{50\,ns}/L_{TOT}$ of fast to total amplitude for the Am-Be- and Pb-sources (top left), for the Am-Be-source shielded with polyethylene (top right), and with 4 cm of lead (bottom left). The contribution from the Pb-source alone is shown in the bottom right figure.**

Figure 1.7: DD-neutron source.

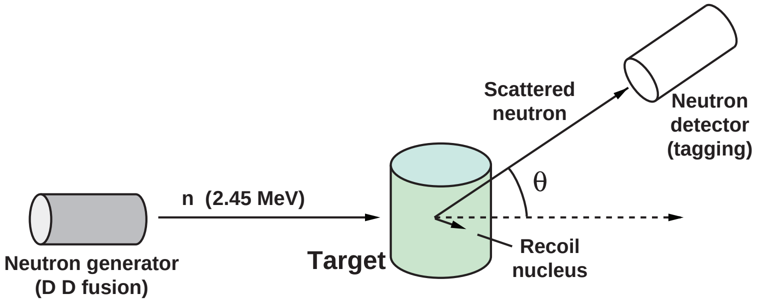

Figure 1.8: Neutron scattering experiment.

around $r$ = 0.8. This can be proven by inserting a 11 cm thick polyethylene absorber, while a 4 cm lead sheet has no effect. The accumulation of events around $r = 0.3$ is due to recoil electrons, the diagonal band due to ADC saturation from $\alpha$'s.

Even small neutron fluxes around 1 MeV are potentially dangerous since the neutron-argon cross section is some 18 orders of magnitude larger than for WIMPs. It is therefore essential to investigate the response of the dark matter detector to neutrons as a function of recoil energy. A decisive advantage of monoenergetic neutrons over radioactive sources (such as Am-Be) is the known incident energy from which the energy transferred to the nucleus can be calculated by measuring the neutron elastic scattering angle.

We have therefore purchased a neutron source from NSD-Fusion GmbH (Fig. 1.7). The source will deliver monoenergetic 2.45 MeV neutrons ($10^7$ $s^{-1}$) from the reaction DD → $\mathrm{He}^3\mathrm{n}$. A sketch of the experiment we intend to perform is shown in Fig. 1.8. The collimated neutrons are scattered by a small liquid argon cell and detected at a given angle $\theta$ by a liquid scintillator counter. We have estimated that, after collimation and using a 10 cm argon cell, we would obtain around 5 counts/s in the neutron detector. The purpose of the experiment is thus to measure the light yield as a function of nuclear recoil energy which differs strongly from that of electronic excitation, due to quenching.

In the 1 t detector the probability for two or more neutron interactions is large enough to be measured precisely. This fraction can be measured with the DD-source and used to reduce the neutron background during WIMP searches, since WIMP interactions do not lead to multiple scattering events.

During 2008 the design of the DD-source was optimised in collaboration with the producer

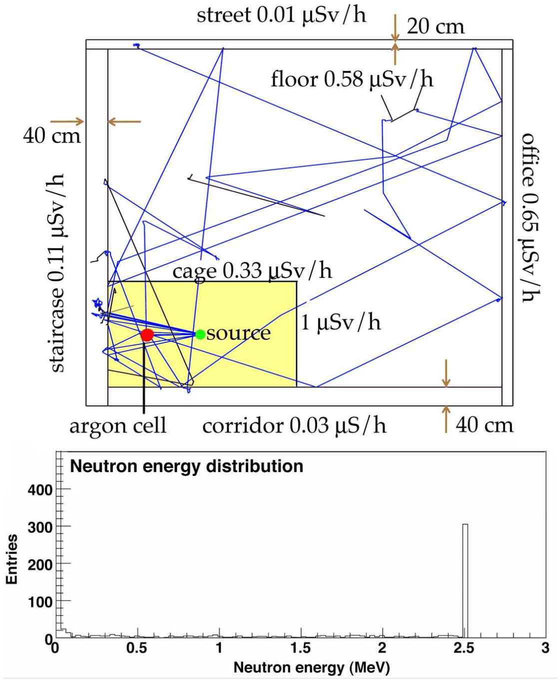

Figure 1.9: Top: predicted dose distribution in our laboratory with the neutron source in operation (the tolerated radiation dose is 2.5 $\mu$Sv/h). The rays are typical neutron trajectories. Bottom: energy spectrum of neutrons at the argon cell.

to fulfill the safety and radiation requirements at CERN, so that the source could be operated in our laboratory close to our offices. We had also to provide our own GEANT4 simulation of the expected radiation levels in and around our laboratory (Fig. 1.9). The apparatus includes a real time ambient neutron dose monitoring system, and components for an operation interlock. A safety fence will be installed to avoid access to the radiation area during operation.

The neutron source, including its 27 mm thick aluminium housing, is surrounded by a 1 m long cylindrical shielding (50 cm of polyethylene). A hole, 10 cm in diameter, provides the collimated beam of neutrons. The neutron energy spectrum of the neutrons exiting the collimator is shown in Fig. 1.9, bottom. About 1.5% of the total neutron flux reaches the argon cell located at 1 m of the source. A fraction of 20% of the neutrons have the initial energy of 2.45 MeV, while 60% are thermalized.

Meanwhile we have purchased a liquid scintillator cell from SCIONIX with a photomultiplier coupled to a 3″ × 3″ cell filled with $C_6H_4(CH_3)_2$, which has a high H:C ratio of 1.21 (Fig. 1.10). This kind of detector is applicable for neutrons above 50 keV and gives information on the neutron energy, since the recoil proton is fully absorbed in the cell. Neutrons can also be separated from $\gamma$-events by pulse shape discrimination. Figures 1.11 and 1.12 show preliminary measurements with the Am-Be-source, displaying the normalized and averaged pulse shapes from electron and proton recoils, and the discrimination power between neutrons and photons.

As mentioned before, the purity in argon (and therefore the scintillation quality) can be monitored by measuring the lifetime of the slow component (6). We have therefore built another small liquid argon cell connected to the 1 t detector (Fig. 1.13). A 10 Bq $^{210}$Pb source for the argon excitation is used to monitor the lifetime of the slow component every 10 s. We

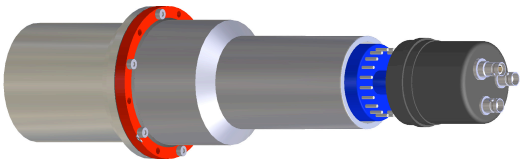

Figure 1.10:SCIONIX liquid scintillator cell.

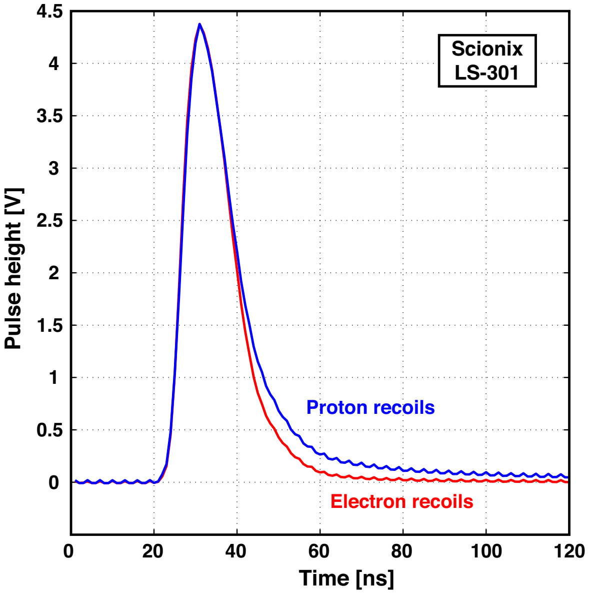

Figure 1.11: Normalized pulse shape from electron and proton recoils.

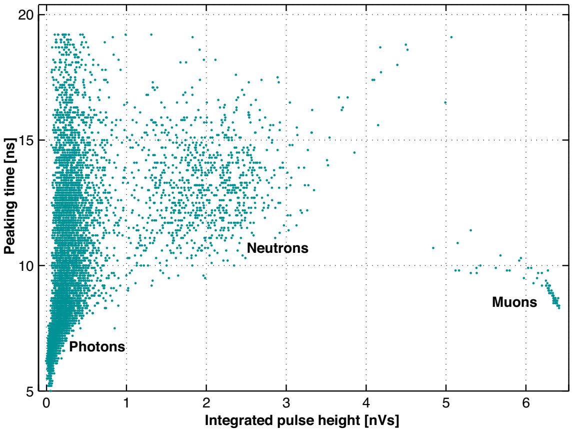

Figure 1.12: Peak-time vs. integrated pulse height measured with the Am-Be source.

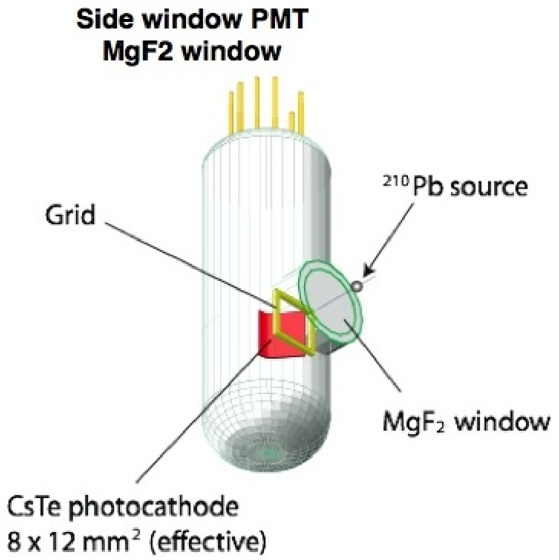

**Figure 1.13: Sketch of the liquid argon purity monitor. A small PMT with VUV sensitive photocathode and a $^{210}$Pb-source emitting both $\alpha$ and $\beta$ are immersed in liquid argon.**

use a small Hamamatsu R8486 PMT with MgF$_2$ window and CsTe photocathode which is directly sensitive to 128 $\mu$m VUV-photons (quantum efficiency 20%) and therefore does not require a WLS. The device (56 mm in diameter and 50 cm high) is rather compact.

The ArDM detector becomes operational in 2009 and will hopefully be moved to an underground location in 2011, following the extensive performance tests which can be most conveniently performed on the surface at CERN.

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