1 Towards a Dark Matter Experiment

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(ArDM Collaboration)

1.1 Introduction

The search for dark matter is one of the most pressing activities in particle physics. Dark matter is probably made of Weakly Interacting Massive Particles (WIMP) which are stable particles trapped in the gravitational fields of galaxies. The favored candidate for WIMPs is the lightest supersymmetric (SUSY) particle, the neutralino with a mass of at least 40 GeV, according to LEP searches. The direct detection of WIMPs involves scattering on target nuclei with recoil energies in the range 1 - 100 keV. The cross-sections are tiny but rate predictions are model dependent, and therefore uncertain by several orders of magnitude. They depend e.g. on the nuclear target (atomic number, spin, form factors) and the type of detector used (energy threshold, resolution, signal discrimination). The search for WIMPS is hence experiment driven. The experimental upper limit for the cross-section of WIMPS with nucleons is about 10^{-6} pb.

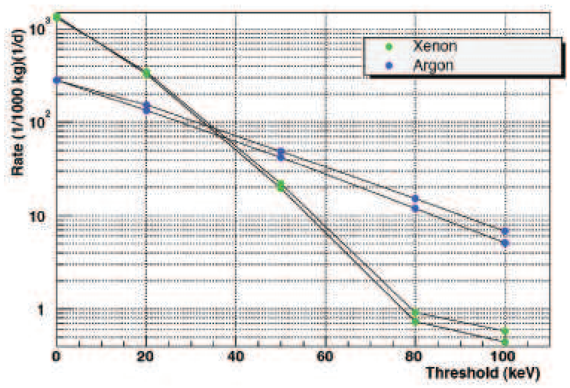

Figure 1.1:
Expected daily WIMP detection rate for a 1 ton detector as a function of threshold for xenon and argon, assuming a mass of 100 GeV and a cross section of 10^{-6} pb. The steeper curve is for xenon.

Noble liquid detectors such as xenon or argon could act as target for WIMP detection. They have high scintillation and ionization yields because of their relatively low ionization potentials. Ionisation electrons *and* scintillation light may be detected (1). Argon is less sensitive to the threshold of the nuclear recoil energy than xenon, because of form factors, and is also much cheaper. Also, recoil energy spectra in xenon and argon are quite different (Fig. 1.1). These liquids are therefore complementary in providing a crosscheck once a WIMP signal has been found.

1.2 The liquid argon detector

We describe here R &D developments for an experiment that could possibly reach a cross-section of 10^{-10} pb. The detector (Fig. 1.2) would contain 1 ton of liquid argon. It exploits the ratio of scintillation to ionisation in argon and the scintillation time discrimination between nuclear and electron recoils. With a nuclear recoil energy threshold of say 30 keV, a WIMP-nucleon cross-section of 10^{-6} pb would yield 100 events per day per ton. Therefore, a 1 ton

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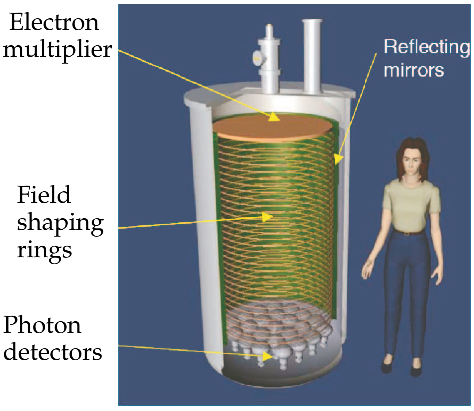


Figure 1.2: Artist's view of the 1 ton ArDM liquid argon detector to search for WIMPS.

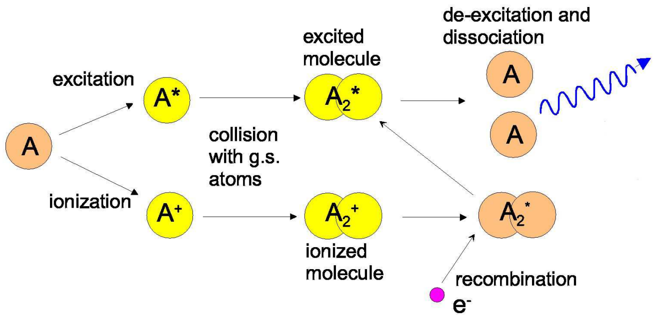


Figure 1.3: The two mechanisms leading to the emission of 128 nm photons are excitation $Ar^* + Ar \rightarrow Ar_2^* \rightarrow Ar + Ar + \gamma$ and ionisation $Ar^+ + Ar \rightarrow Ar_2^+ + e^- \rightarrow Ar_2^* \rightarrow Ar + Ar + \gamma$. The energy required to generate a photon is 68 eV.

argon detector could improve significantly on the upper limits, provided that the threshold of 30 keV and sufficient background rejection can be achieved. A drawback of natural argon liquefied from the atmosphere is namely the radioactive β-emitter ^{39}Ar. Its activity in atmospheric argon has been measured to be about 1 Bq/kg (2). It therefore induces a background rate of about 1 kHz in a 1 ton detector. The first milestone in the design of an experiment is therefore the optimization of the light detection from nuclear recoils and and the rejection of the γ and β background. Figure 1.3 shows the two mechanisms leading to the emission of 128 nm light in argon.

The concept of WIMP detection in argon is shown in Fig. 1.4. Primary scintillation light from argon and secondary charge signals are read independently. Following an ionizing event, ionization charges drift towards the top of the detector where they are extracted from the liquid to the gas phase. An electron multiplier system then amplifies the electrons to produce a detectable signal. The ratio of the scintillation to the ionization yields is extremely high for WIMP events, due to quenching. Very high drift fields up to 5 kV/cm must be reached to detect an ionization signal from highly quenched nuclear recoils.

Because background discrimination requires a high ratio of scintillation to ionization yields, the VUV scintillation light needs to be detected efficiently. This is the main task and responsibility of the Zurich group. We are also investigating alternative schemes to photomultipliers, such as wavelength shifters read out by avalanche photodiodes (APD).

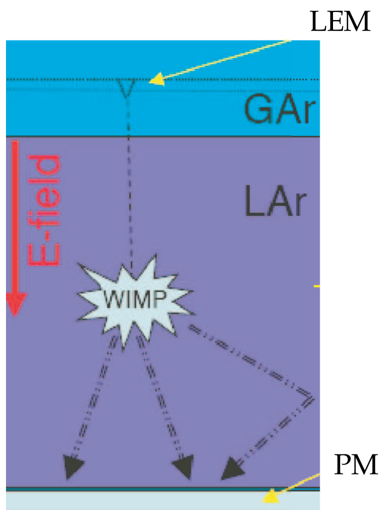


Figure 1.4: Principle of WIMP detection in liquid argon (LAR). WIMPs lead to a high ratio of primary scintillation light detected by the photomultipliers (PM) to charge collected by the electron multiplier (LEM) in gaseous argon (GAR).

1.3 Light collection

Monte Carlo simulations suggest that a light collection efficiency of at least 5% for 128 nm photons will be required to suppress the background from ^{39}Ar β-decay. However, VUV photons are absorbed by most materials, with few exceptions such as MgF_2 and LiF. A large area coverage using phototubes with MgF_2 windows is excluded for cost reasons. Also, the operation of phototubes at cryogenic temperatures requires photocathodes with a metallic underlayer to prevent electrical charge-up.

However, 128 nm light can be reflected or wavelength shifted. We have therefore investigated aluminized mylar foils with MgF_2 coating and Tetratex (porous teflon) foils as specular or diffuse VUV-mirrors (3). The reflecting material is mounted on a rotating frame in the test box immersed in clean gaseous argon at NTP (Fig. 1.5). The gas atoms are excited by α- particles yielding 68 eV/ emitted photon and leading to tracks of typically 5 cm length. An APD is used as the trigger. Direct and reflected photons are measured by another large area APD (15 mm in diameter) with a wide spectral range. The reflection coefficient is derived from the measurement by Monte Carlo simulation of the acceptance, as a function of mirror angle φ. These results are shown in Fig. 1.6, superimposed to measurements from literature. For Al + MgF_2 we obtain a reflectivity of 91.5% and for Tetratex 95%. The high reflectivity of Tetratex is probably due to the fluorescence of teflon in the yellow region.

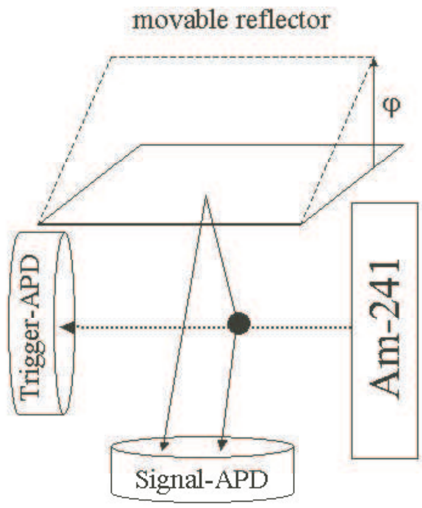
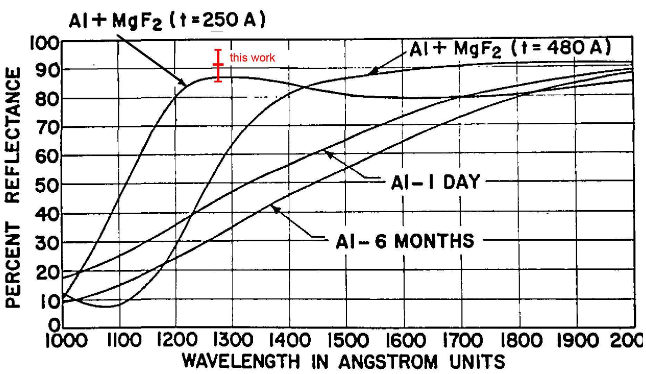


Figure 1.5: Setup used to measure the reflectivity of various coated mirrors.

Large area APDs (from Advanced Photonics) with very thin entrance windows read the 128 nm light. Their quantum efficiency is about 60% at 128 nm (6). However, their small active area require a method for light concentration. We have therefore investigated wavelength shifters bound to light guides with filling materials such as polystyrene (7). Preliminary



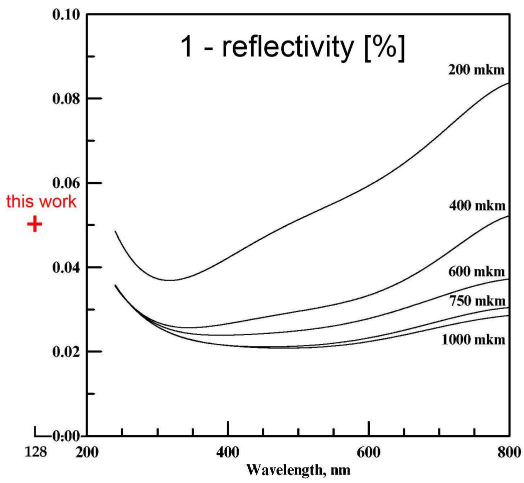


Figure 1.6: Reflectivity of Al + MgF_2 (above, from ref. [4]) and Tetratex (right, from ref. [5]), compared to our own measurements.

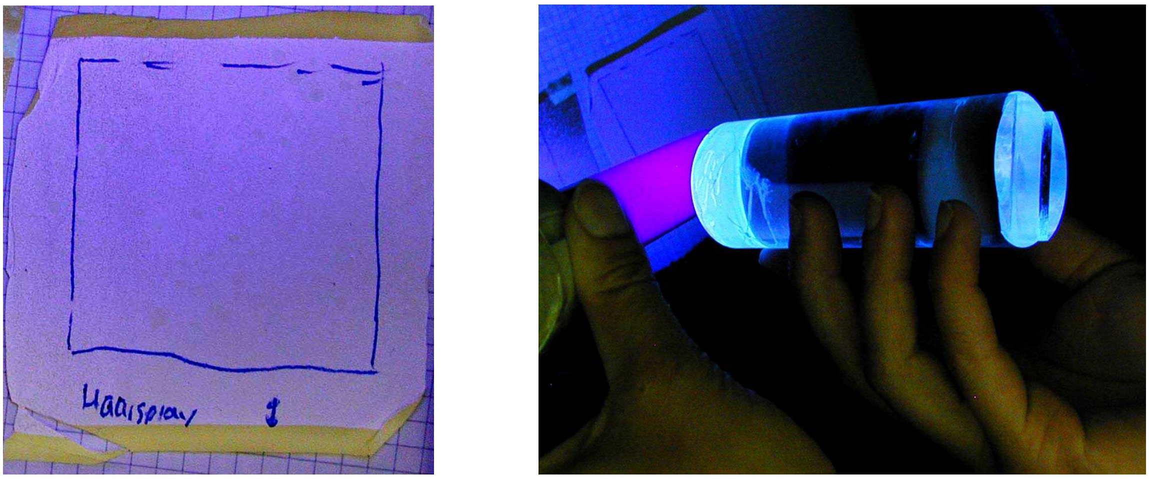


Figure 1.7: Reflection of UV light on teflon coated with TPB (left) and emitted light (right).

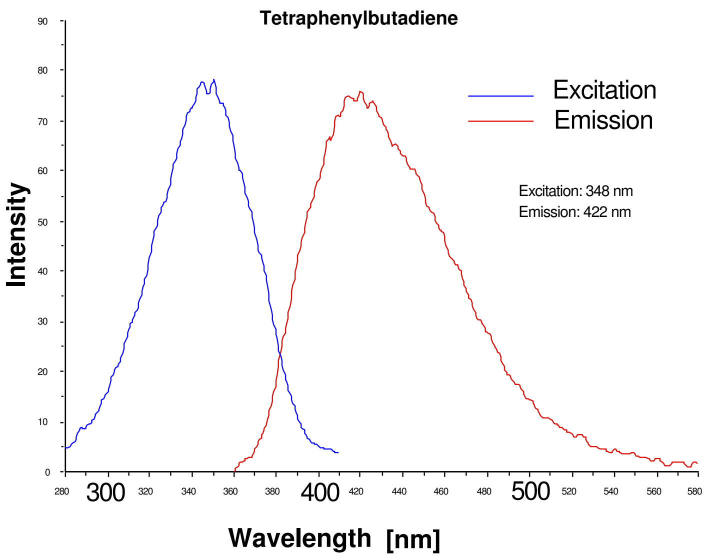


Figure 1.8: Absorption and emission spectra of TPB.

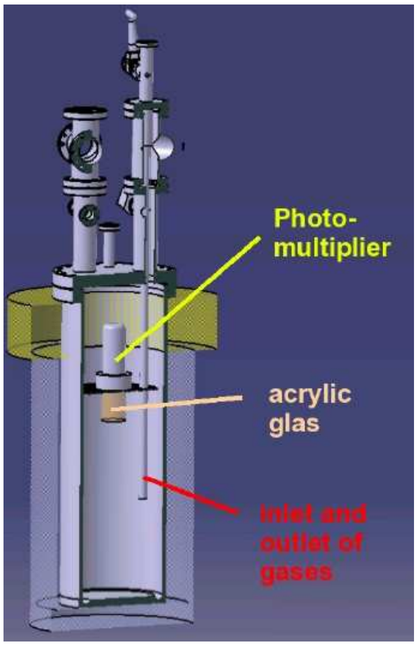


Figure 1.9: Vacuum chamber.

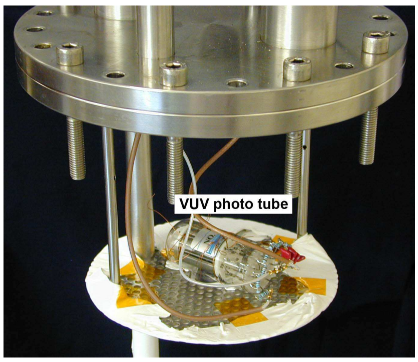


Figure 1.10: Vacuum chamber with VUV tube.

tests with Tetratex foils or acrylic glass coated with wavelength shifters give promising results. Figure 1.7 shows two samples illuminated with 250 nm UV light. The white-bluish centre of the Tetratex sample (left) was coated with tetraphenylbutadiene (TPB) dissolved in chloroform before being sprayed on the teflon tissue. The absorption maximum of TPB is around 340 nm, its emission maximum around 420 nm (Fig. 1.8). The yellow fluorescence of the uncoated teflon can be clearly seen around the borders. Figure 1.7 (right) shows a TPB/polystyrene mixture applied to one end of a plexiglas cylinder, which demonstrates trapping of the emitted light at 420 nm from TPB.

To test functionality and measure light yields, decay times, outgasing and other properties, we have built a 7 ℓ vacuum chamber which can be filled with gaseous or liquid argon (Fig. 1.9). The chamber will also be used to search for the ^{39}Ar signal. A gas purification system filters out residual water or oxygen traces, both being strong UV absorbers. The gas composition is monitored by a quadrupole mass spectrometer with high sensitivity (10^{-10}) connected through a dosing valve. Figure 1.10 shows the top flange holding a small VUV phototube (1 cm^2 Cs-Te photocathode) with MgF_2 window. This device has a narrow spectral response (115-320 nm) and a well known quantum efficency ($\sim$ 25%) and is therefore mainly used for calibration. Figure 1.11 shows a standard bialkali photomultiplier (2", 300-600 nm) mounted on the flange for the first spectroscopical measurements.

Figure 1.12 shows an intensity spectrum from 5.3 MeV α's emitted by a ^{210}Po source in argon gas at NTP. With a total coverage of the inner wall with TPB coated Tetratex we could obtain 885 photoelectrons (p.e.), corresponding to a detection efficiency of roughly 1%, which is already encouraging for a large detector. This setup should be able to detect the ^{39}Ar decays with a mean energy deposit of 218 keV (corresponding to 30 p.e.).

However, as Fig. 1.13 shows, the number of photoelectrons depends crucially on the purity of argon. The data sample at a partial air pressure of 2×10^{-6} mbar was selected to analyze the time evolution of the light output in gaseous argon. The signal amplitude is shown as a function of time in Fig. 1.14. One clearly observes two components which correspond to the decay of the singlet and triplet molecular states. The data were fitted by two exponential functions convoluted with a Gaussian to describe the time resolution. The fast component has a mean life of 15.7 ± 4.0 ns, the slow component a mean life of 3.12 ± 0.08 μs. The latter agrees with the published value 3.2 ± 0.3 μs (9).

Figure 1.11: Bialkali tube with reflector.

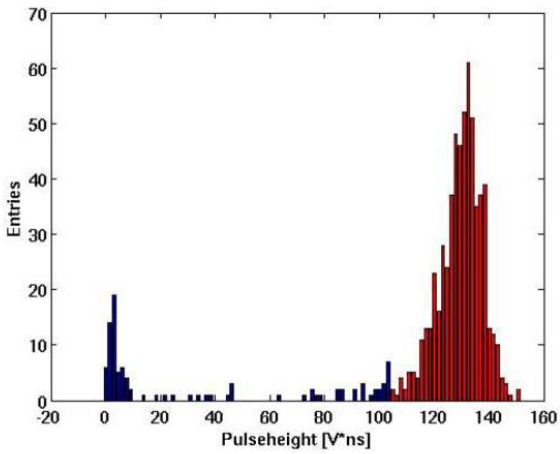


Figure 1.12: Intensity distribution of the 128 nm light measured in gaseous argon.

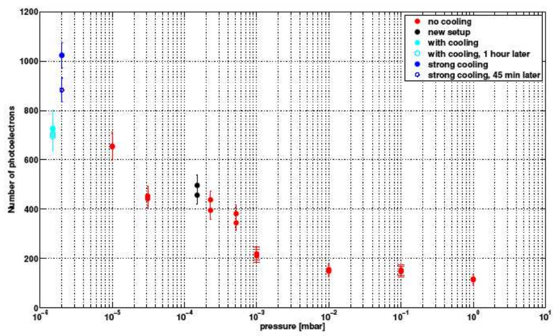


Figure 1.13: Number of photoelectrons as a function of residual partial air pressure measured for different experimental conditions (from ref. [8]).

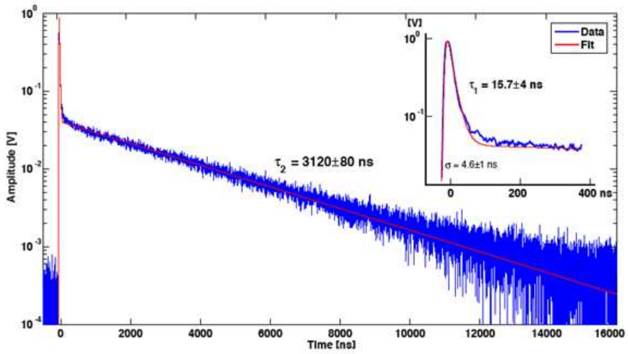


Figure 1.14:
Intensity as a function of time showing the fast and slow components of scintillating argon (from ref. [8]).

These developments will be pursued in 2006 with liquid argon. We will then investigate the performance of APDs using focussing Winston cones. Assuming that enough light can be detected we will then formally propose a dark matter experiment e.g. in the underground Canfranc Laboratory in Spain. We have already expressed our interests to the corresponding Scientific Committee.

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