1 Towards a dark matter experiment

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The interaction of Weak Interacting Massive Particles (WIMPs) with nuclei in a dark matter detector generates recoil energies below typically 100 keV. The differential cross section decreases exponentially with increasing recoil energy. This makes WIMP detection difficult due to the low energy background. Hence massive detectors with low detection thresholds are needed, among them cryogenic ones using noble liquids such as liquid argon (LAr). The Zurich group has designed and built the light readout system for the 1 ton LAr detector ArDM which is being developed at CERN. Details on the detector can be found in previous annual reports and in recent publications [1–4].

The ArDM detector was filled for the first time with 1 ton of LAr in 2009. Several important parameters such as stable cryogenic operation in high LAr purity, high scintillation light yield, and detection of events down to energies of tens of keV's could be verified. The test was performed with a partial light readout assembly consisting of half of the PMT's[1], no electric field and no charge readout. The LAr purity was found to be constant over the measurement time of three weeks by monitoring the decay time of the slow component of the light signal [3].

The measurements were done with external sources such as ^{22}Na, delivering positrons (annihilating into two 511 keV γ's) and monochromatic 1275 keV γ's. The light yield produced by one of the 511 keV γ's, following (multiple) Compton scattering, was measured by triggering with a 4" Na(Tl) crystal on the second 511 keV emitted in the opposite direction, and on the 1275 keV γ. Figure 1.1 shows the light yield distributions for the source located at two different vertical distances to the photomultiplier array [3]. The simulated distribution is shown for comparison. Good agreement is found with an average light yield of typically 0.4 p.e./keV, which is roughly half of the yield that would be obtained with a completed detector (14 PMT's)[2]. We are therefore confident to be able to reach our goal of 30 keV threshold in ArDM for WIMP detection.

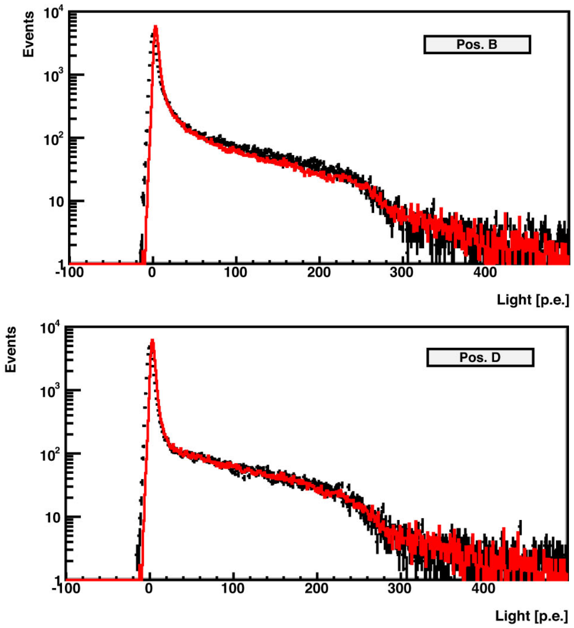

Fig. 1.1 – Light yield in the 1-ton LAr detector for 511 keV γ's (in photoelectrons, p.e.) at two positions of the ^{22}Na- source. The measurements are in black, the simulated data in red.

The light yields of nuclear recoils in LAr are poorly known, especially below 50 keV (see e.g. ref. [5]). A suitable way to produce nuclear recoils of known energies in the lab is n-Ar elastic scattering with monoenergetic neutrons, detecting the neutron as a function of scattering angle. We have therefore

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[1] 7 Hamamatsu R5912-MOD 8" PMT's with Pt-underlay

[2] Due to quenching the light yield for nuclear recoils in the few 10 keV range is ≈30% lower than for electrons (Fig. 1.9).

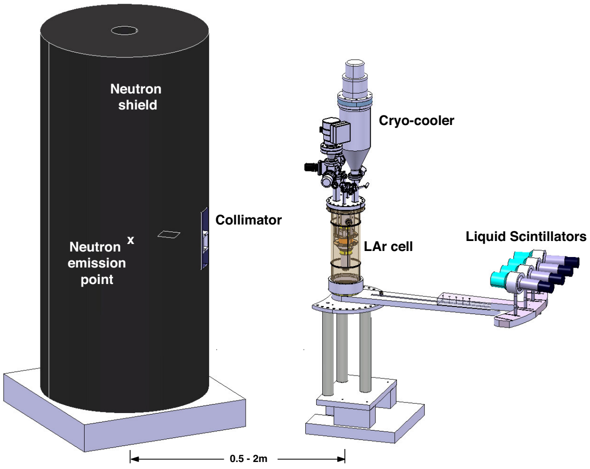

Fig. 1.2 – The neutron generator with polyester shielding, the LAr cell, the cryocooler and the four liquid scintillators detecting the scattered neutrons.

set up a scattering experiment with collimated 2.45 MeV neutrons from our $dd \rightarrow {}^3$He n source [6]. The target is a small ($<1\ell$) test cell (77 mm high and 74 mm in diameter) and liquid scintillation counters (LSC, EJ301 from SCIONIX) detect the scattered neutrons in coincidence as a function of scattering angle (Fig. 1.2). To reduce the measurement time we use four LSC's to cover various angles in parallel.

The fusion chamber is surrounded by a 90 cm diameter shield of borated polyester and the experiment confined within a radiation controlled fence in our laboratory at CERN. Residual radiation (mainly from scattered neutrons and X-rays) is well below the authorized limit of 2.5 μSv/h. The neutrons are collimated through a polyethylene orifice within roughly 1% × 4π sr. The neutron flux (up to 5×10^6 n/s in 4π according to specifications) is controlled through the applied high voltage and discharge current.

The neutron flux was measured with a 5" LSC located at the collimator exit. The polyethy lene collimator was surrounded by a 2 mm thick lead box against X-rays inserted into the polyester shielding. According to NSD-Fusion, the highest possible voltage and current are 100 kV, resp. 15 mA, corresponding to a flux of 10^7n/s into 4π. The flux increases proportionally to the current and to the voltage $V^{2.8}$.

Measurements were made with and without polyethylene collimator and the rates corrected for the solid angle, assuming a detection efficiency of the LSC of 80%. A NIM MPD-4 module was used to discriminate between neutrons and X-rays. Figure 1.3 shows the measured neutron intensity (blue, red and orange points) compared with the values specified by NSD-Fusion (green crosses for 10mA and orange crosses for 15mA [6]). Insufficient lead shielding leads to a strong X-ray contamination. The measured flux was roughly one order magni-

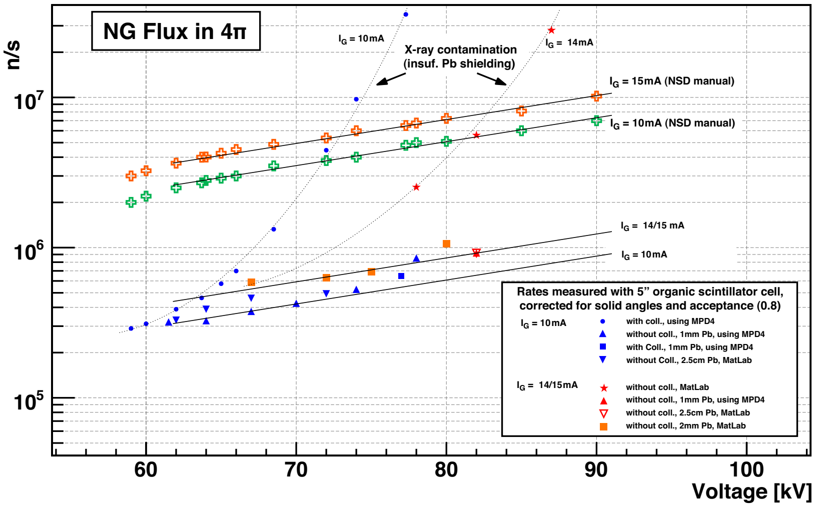

Fig. 1.3 – Neutron generator flux into 4π (see text). Lines are drawn to guide the eye.

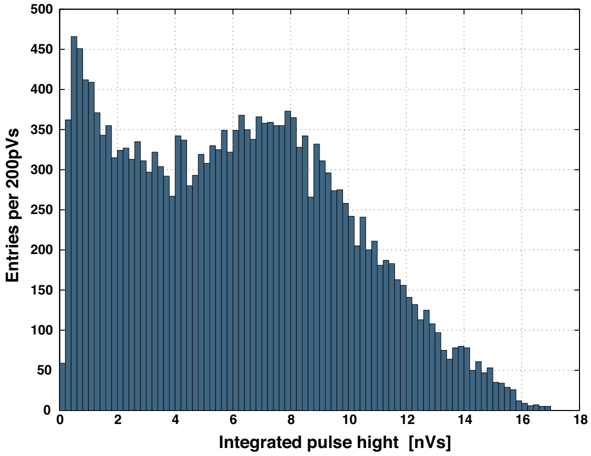

Fig. 1.4 – Raw neutron spectrum.

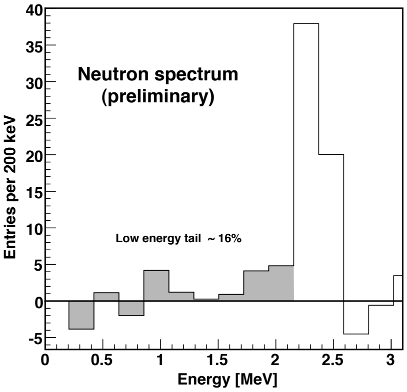

Fig. 1.5 – Neutron energy spectrum obtained by unfolding the response of the LSC.

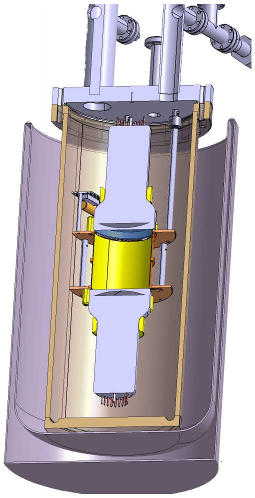

Fig. 1.6 – LAr cell with its 2 PMT's on top and bottom of the LAr volume.

tude smaller than anticipated, with a maximum of 10^6 n/s. However, the generator was upgraded recently by NSD-fusion, leading to a factor 2 − 3 improvement in neutron flux.

The neutron energy distribution (smeared by collimator scattering) must be known to measure the light yield from LAr accurately. Figure 1.4 shows the neutron energy distribution measured by a 5" LSC placed at the exit of the collimator. Ideally the spectrum should be flat without collimator scattering, infinite resolution and single n-scattering. The spectrum of Fig. 1.5 was obtained by unfolding the response of the LSC. The latter was obtained with an AmBe-source, by measuring the neutron energy through the time-of-flight between the source and the neutron counter over a distance of 1 m. The start time was determined from the 4.4 MeV γ detected in a BGO crystal located close to the AmBe-source.

We have started to measure the scintillation response of LAr to nuclear recoils with the LAr cell shown in Fig. 1.6. Wavelength shifting reflectors (Tetraphenyl-Butadiene, TPB, on Tyvek foils) were mounted on the inner walls of the cell to convert the 128 nm light into 400 nm. The cell was read out by two Hamamatsu R6091-01MOD PMT's with platinum underlay for cryogenic operation. An internal ^{210}Pb-source emitted 5.3 MeV α's and up to 1.2 MeV electrons. The component ratio CR is defined as the ratio of integrated light yield during the first 50 ns to the total light yield. Thus a high CR corresponds to the emission of light with mainly the fast component. Heavily ionizing particles such as α's or nuclear recoils lead to a large CR value [7]. Figure 1.7 shows the component ratio CR from one of our first measurements of argon luminescence with the fusion generator. A clear contribution from neutron induced nuclear recoils is observed at $CR \sim 0.8$.

A first measurement of the scintillation efficiency for nuclear recoils relative to electrons was performed with a 5" LSC at 65° from the incident beam direction, at a distance of 50 cm from the LAr cell. The time-of-flight between the LAr cell and the LSC's could be determined off-line and used to remove background, e.g. from multiple neutron

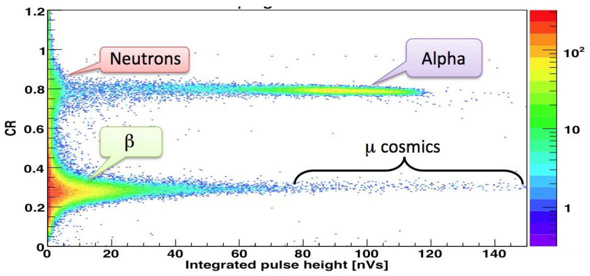

Fig. 1.7 – Component ratio CR in LAr for 2.45 MeV neutrons, 5.3 MeV α's and 1.3 MeV electrons and cosmic muons.

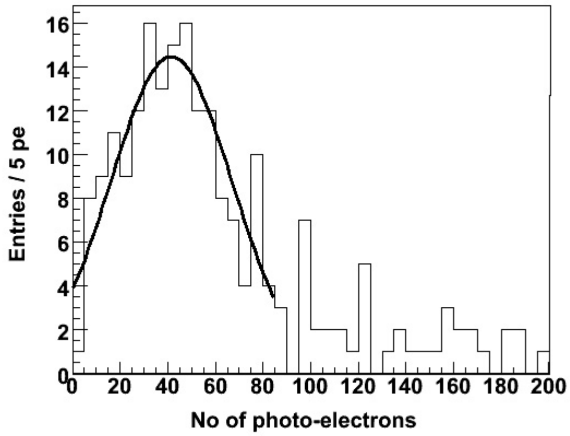

Fig. 1.8 – Integrated pulse height distribution in the LAr cell for neutron scattering at 65°.

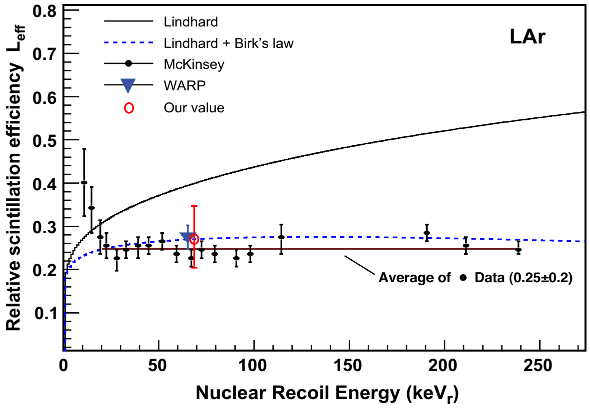

Fig. 1.9 – Relative scintillation efficiency in LAr as a function of recoil energy (from ref. [5]). Our preliminary result is shown by the red data point.

scattering in the cell. The reference time was determined with a Na-source located at equal distance from the LAr-cell and the LSC, and using the two back-to-back 511 keV γ's. At 65° the argon recoil energy is 69 keV with 2.45 MeV incident neutrons. This corresponds to a time-of-flight of 23 ns for 2.4 MeV neutrons flying to the LSC. Good pulse shape separation between proton and background (γ-induced electron recoils) could be achieved with the LSC by analogue pulse shape discrimination.

Several cuts were applied in the offline analysis. For example, we required the component ratio CR to be larger than 0.6 (see Fig. 1.7). We also rejected events close to the PMT windows by comparing the signals from the two PMT's. A time-of-flight window between 18 and 31 ns was selected. Figure 1.8 shows the pulse height distribution in LAr for 69 keV recoils. We obtained a scintillation efficiency of 0.27 (with about 25% error) in this first attempt. Figure 1.9 shows our data point compared with data from ref. [5].

Light yields of nuclear recoils are usually determined relative to electronic recoils. The electronic light yield is determined with various external γ-sources and also with a $^{83}\mathrm{Kr}^{m}$ source which can be connected directly to the gaseous phase in our setup. We use a linear dependence on energy between 60 and 1062 keV, but are working on a calibration at the 122 keV line from ^{57}Co, as is the standard in the field. To improve the light yield and the measurements with radioactive sources we upgraded our LAr cell to reduce the thickness of the stainless steel vessel and the LAr volume. Tetratex foils[3] were used instead of the Tyvek reflectors, and TPB-Paraloid coating was replaced by 0.08 mg·cm^{-2} of evaporated TPB. Figure 1.10 shows the spectrum of the 60 keV line from Am-decay. During data taking the mean life of the the slow component was much lower than the established value of 1.6 μs, due to the impurity of the LAr (see e.g. ref. [3]). By extrapolating the light yield to maximum purity we could set a lower limit of 3.2 p.e./keV.

Most of the mechanical components for the final measurements are now installed in our laboratory. During the next months we will commission the gas handling system and the cryocooler (Gifford-McMahon-type) mounted on top of the LAr cell. A cooling serpentine is bonded to the temperature regulated cold head and provides the liquefaction of the recirculated gas. Gas purification is achieved by two cleaning cartridges. They reduce the O_2 and H_2O contamination in the gas below 20 ppm. A second air blower has been installed for the neutron generator to operate at maximum power. The completed system will be operational by summer 2011, ready for data taking during several weeks to accumulate enough statistics at various scattering angles. A further upgrade of the LAr cell with a smaller active volume (and less surrounding material) to reduce multiple scattering and enhance the light yield is also foreseen.

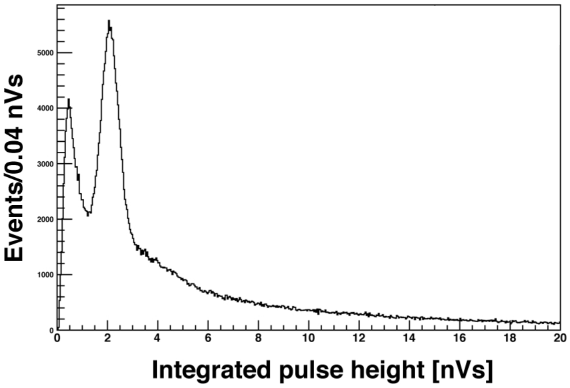

Fig. 1.10 – Energy spectrum from Am-decay measured with the refurbished LAr cell, showing the 60 keV line.

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