Detection of VUV scintillation light in one ton of liquid argon

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In the framework of the ArDM project, a next-generation one ton liquid argon WIMP detector, we built a 5 litre prototype chamber. This setup is primarily used to develop the appropriate read out for argon VUV scintillation light (128 nm) using wave length shifting dyes. The final aim is a energy threshold of 30 keV corresponding to yield of roughly 2% for detected photo-electrons. Beside light yield studies we investigate purity effects as well as background suppression power from the light pulse shape.

Keywords: WIMPs; Liquid argon; VUV light; Triplet state quenching.

1. Introduction

The ArDM project was initiated in 2004 [1,2] with the aim to build a combined liquid argon TPC and calorimeter for the detection of WIMP recoils on a target mass around one ton. Free charge as well as the VUV scintillation light should be recorded with high efficiency to reach an order of 10^9 for the suppression of electron (background) versus nuclear recoil events. This should be achieved by the combined measurement of the charge to light ratio, the time structure of the light, the interaction position and the topologic information on a event-by-event base. β decays of ^{39}Ar, present in ^{40}Ar at a concentration around 10^{-15} [3], are supposed to be the dominant background and the main trigger source[a]. The fast and possible selective event trigger will be derived from the light readout.

The working principle of the bi-phase detector is shown in figure 1 (left). A WIMP interaction with liquid argon at 30 keV produces about 400 VUV photons together with a few free electrons. The strong vertical electric field sweeps the charges to the top of the liquid and extracts them into the

[a] roughly 1 kHz in one ton of liquid argon

gas phase. After multiplication ($\approx 10^5$) in a two stage LEM[b] the charges are collected by a segmented anode. The VUV light is emitted isotropically from the interaction point and converted to blue light by wavelength shifter (WLS) on the side walls. At the bottom of the cryostat the shifted and reflected light is collected by 14 8" phototubes immersed in the liquid. The 3D CAD sketch (fig. 1 right) shows the mechanical design of the prototype detector and the cryostat. Not shown is the foil inside the field shapers with the applied wavelength shifter.

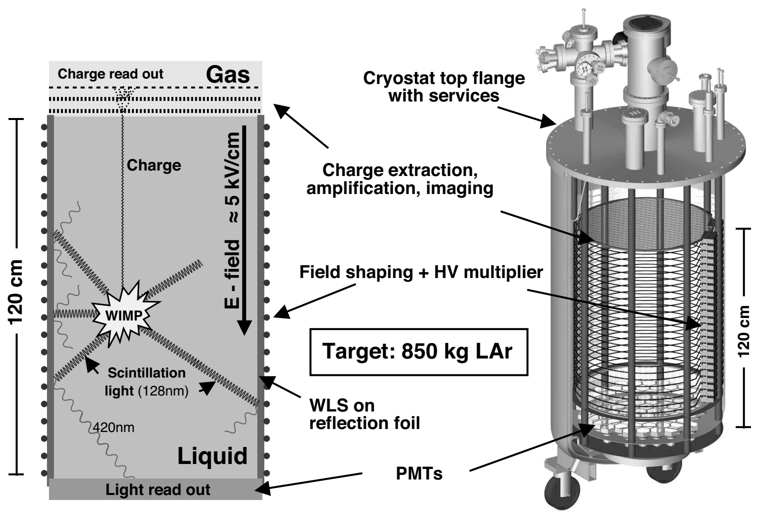


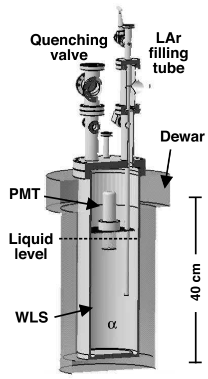
Fig. 1. *Detection principle and 3D drawing of the ArDM detector*

2. Test setup and measurements

A $5\,\ell$ cylindrical chamber (diam. 150 mm, no internal electrical field) was constructed with a variety of service connections (fig. 2 left). Without baking a typical vacuum of 10^{-5} mbar is reached (over 24 h) with a $60\,\ell$/s turbo pump. The residual gas is mainly composed of water. When the chamber is filled with liquid argon it is placed inside an open dewar with LAr for cooling. A 40 Bq internal ^{210}Pb source (5.3 MeV α, 1.2 MeV β) is used for the excitation of argon atoms. In argon gas at NTP α particles are fully absorbed, β particles only partially. Scintillation light and free charges are produced in the complex interplay of ionisation, excitation, recombination

[b]Large electron multiplier

and quenching [4–8] depending on the ionisation density. This leads to singlet and triplet argon eximers which decay radiatively (128 ± 5 nm) with two distinct decay times (τ_1,τ_2). The produced VUV photons are not absorbed by atomic argon and are inherently difficult to detect. Therefore we use optically active materials like TPB[c] for shifting the light into the blue (420 nm), which is well matched to the response of bialkali photocathodes. The wavelength shifter (WLS) material can either be dissolved and sprayed or evaporated on foils on the vessel walls. The optimum application technique and substrate material is the subject of developments, including different low temperature PMTs, which are fabricated with a thin Pt underlay. Presently we investigate two 3” prototypes, a square 8-dynode tube from Hamamatsu (R6237-MOD) and a round 12-dynode tube from ETL (D750UKFLB). The phototubes are placed in the upper part of the vessel being immersed in the liquid. To improve the overall light yield the



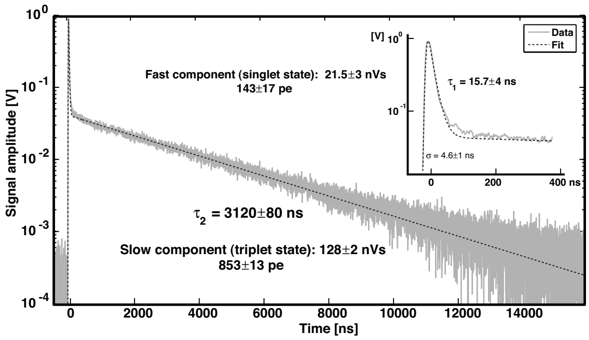


Fig. 2. *5 ℓ test setup and averaged signal of α particles in clean argon gas*

glass window of the phototubes can also be coated with WLS. However this operation is of minor importance since only a small fraction of VUV photons will hit the PMTs directly (Monte Carlo studies).

Liquid argon used for the measurements is delivered at an unspecified level of quality from Carbagas, Switzerland. Argon gas is taken from 50 ℓ cylinders of class Ar 60 (impurities ≤ 1.3 ppm [9]). A re-circulating gas cleaning system is under construction, while oxisorb (CuO) and hydrosorb (molecular sieve) cartridges can be used during filling[d].

[c]Tetraphenyl-butadiene, also P-terphenyl (PTP) is commonly used
[d]Hydrosorb is only used for filling with gaseous argon

The analogue signal from the PMT is sampled by a 1 GS/s digital oscilloscope (20 kS), stored to hard disk and analysed offline. A baseline correction is done with the fraction of the signal before trigger time. The noise is determined by the input amplifier (50 Ω) and shows a $1/f$ spectrum. The number of detected photons is calculated by dividing the integrated signal (charge) by the average single photon charge, which we find from distributions of dark counts and LED light pulses. Figure 2 (right) shows a semilogarithmic representation of 500 averaged α events taken in clean argon gas, the inset is a zoom of the first 400 ns. The dashed line represents a fit to the data by the sum of two exponential decays convoluted with a gaussian. A 6th free parameter was used to fit the event time t_0. The exponential decays model the light from singlet (fast) and triplet (slow) eximer states. From several measurements we find an average value for triplet to singlet yield $R = 6 \pm 1.8$, valid for 5.3 MeV α in argon gas at NTP. The error was estimated from fluctuations among the data sets. The largest measured value for the triplet decay time $\tau_2 = 3120$ ns was found for purest argon gas. This is in good agreement with literature (3200 ± 300 ns) [10].

3. Quenching of the triplet state luminescence

Impurities in argon gas were found to reduce the scintillation light by shortening the decay time τ_2. This effect was studied in detail by mixing argon

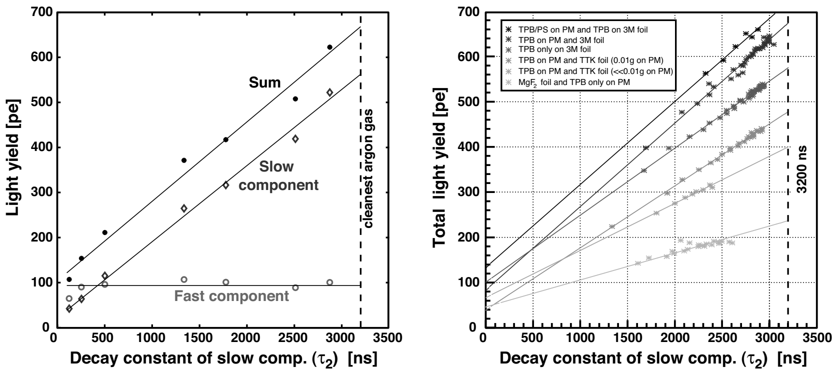


Fig. 3. *Number of photoelectrons (pe) versus decay time* τ_2

gas with air at partial pressures from 1 down to 10^{-6} mbar [11]. For the different air admixtures the averaged α signals were fitted and analysed as described above. Fig. 3 (left) shows the yields obtained for fast, slow and total light, plotted against the fit parameter τ_2. The data points of the slow component exhibit a linear increase with τ_2, while the fast component remains constant. We explain this behaviour with a non radiative destruction of the triplet eximer states by the gas impurities. This is presumably due to residual water, since cooling improves on the light yield (and τ_2). The linear relationship between the light yield and τ_2 is the nature of a PDF for an exponential decay. No evidence is found for a change of R nor for significant absorption of VUV light by the gas impurities.

These results establish our light yield calibration and allow for substantially faster measurements by simply flushing the vessel with argon gas without prior evacuation of the air. As an example, fig. 3 (right) shows measurements done with different coatings and reflectors. Knowing the yield of VUV photons (78 k per α particle [12]), we find the yields of the different designs by extrapolating to $\tau_2 = 3200$ ns.

A similar correlation of light yield and τ_2 seems to be present in liquid argon and is subject to current investigations. However stronger VUV absorption is expected due to the higher densities.

4. Measurements in liquid argon

Due to the high stopping power of liquid argon both, α and β particles from the ^{210}Pb source can be seen in the small setup. They cause different ionisation densities, hence show different values for R and light yield[e].

This effect was first observed in a measurement with TPB coated Teflon mesh (Tetratex) on the side walls of the test chamber. Since a low temperature PMT was not yet available we used a standard bialkali PMT (heated) with an acrylic light guide plunged into the liquid argon. Events from the internal ^{210}Pb and external γ source were recorded for several hours and analysed as described above. The signals were again found to be described by the sum of two exponential decays. A value of about 800 ns was measured for τ_2. Two populations of event types were identified, differing in the ratio R of triplet to singlet states. We identify these groups with signals from α ($R = 0.2$) and β particles ($R = 1.7$). The data are shown in fig. 4. The upper histograms are pulse height spectra (total light) of the ^{210}Pb source alone (left) and including an external γ source (right). The left peak is attributed to β and the right to α events. From the distribution means we find a quenching factor of about 0.4 for α particles. The lower plots add the information from the pulse shape to the ordinate, calculated from the

[e] Quenching: α particles lead to similar light yields as nuclear recoils

fraction of fast (<50 ns) to total light. The two islands for α and β events are already well separated despite a modest light yield (0.4%).

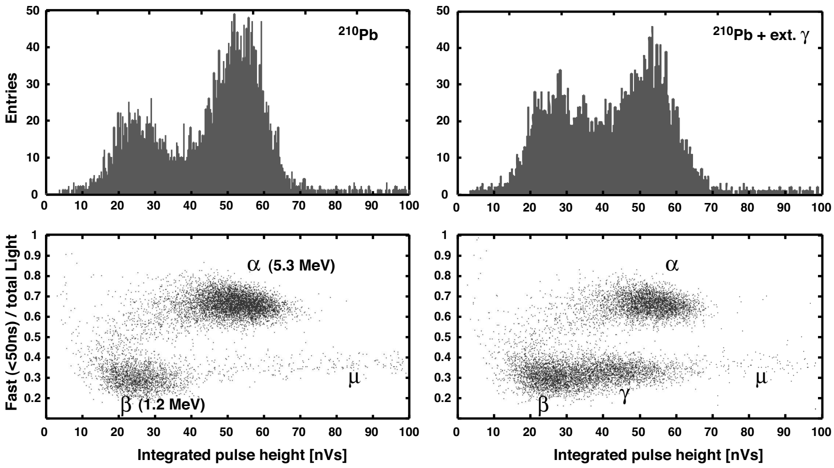


Fig. 4. *Signals in liquid argon, without (left) and with external γ source (right). The upper plots show the integrated pulse height spectra, the lower plots show the ratio of fast (<50 ns) to total light versus the integrated pulse height.*

5. Conclusions

Our R&D results for the VUV light yield are rather encouraging for a large detector volume. The goal is to reach 2%, while 1% has already been achieved. The acquired experience allows us to start the construction of the one ton prototype in 2007.

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