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DarkSide search for dark matter

The DarkSide collaboration

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ABSTRACT: The DarkSide staged program utilizes a two-phase time projection chamber (TPC) with liquid argon as the target material for the scattering of dark matter particles. Efficient background reduction is achieved using low radioactivity underground argon as well as several experimental handles such as pulse shape, ratio of ionization over scintillation signal, 3D event reconstruction, and active neutron and muon vetos. The DarkSide-10 prototype detector has proven high scintillation light yield, which is a particularly important parameter as it sets the energy threshold for the pulse shape discrimination technique. The DarkSide-50 detector system, currently in commissioning phase at the Gran Sasso Underground Laboratory, will reach a sensitivity to dark matter spin-independent scattering cross section of 10^{-45} cm^2 within 3 years of operation.

KEYWORDS: Noble liquid detectors (scintillation, ionization, double-phase); Dark Matter detectors (WIMPs, axions, etc.)

2013 JINST 8 C11021

Contents

2013 JINST 8 C11021

1 Introduction to the DarkSide program

The DarkSide program searches for interactions of a not yet identified non-luminous form of massive and cold matter, so called cold dark matter, in liquid argon (LAr) at Laboratori Nazionali del Gran Sasso (LNGS). It is a staged approach with two-phase LAr time projection chambers (TPCs) at 50 kg and 3.3 ton active target mass scale. A particle interacting in LAr creates both scintillation light and ionization electrons. In a two-phase LAr TPC, the ionization electrons are drifted by means of an applied electric field and extracted from the liquid into the argon gas pocket (GAr) where they are accelerated to produce an amplified secondary scintillation signal via a process known as electroluminescence. The primary scintillation signal (S1) and the secondary scintillation signal (S2) are both measured with two arrays of photomultiplier tubes (PMTs), one below and one above the target volume (see figure 1). These two signals allow the three-dimensional localization of events and the ability to fiducialize the target volume, yielding an inner core with a very low background. The position of an event is obtained from drift time of the ionization electrons, given by the time difference between the S1 and S2 signals, and the distribution of the S2 signal on the top PMT array. Argon scintillation light is produced by the formation and radiative decay of singlet and triplet dimer excited states with $\sim$7 ns (fast) and $\sim$1.6 μs (slow) scintillation decay times, respectively [1]. The intensity ratio of the singlet to triplet state depends on the deposited energy density which is different for nuclear recoils created by dark matter or neutron interactions and electronic recoils produced by β and γ-rays. The resulting difference in pulse shape can be exploited to suppress electronic recoils to levels in excess of 1 in 10^8 [2].

To test the concept and verify the achievable energy threshold and background rejection, a detector with a fiducial mass on the order of 10 kg (DarkSide-10) was developed and operated at Princeton University and LNGS. Description of the detector and the light yield study under zero field operation during the first underground data run are reported in details in [3]. Only a short overview of the relevant parameters and the observed light yield for different runs is presented here (see table 1).

The first physics detector in the DarkSide program, DarkSide-50, is currently being commissioned at LNGS. The DarkSide-50 TPC with underground LAr, strongly depleted in ^{39}Ar radioisotope, is coupled with a 4 m borated liquid scintillator neutron veto and a 10 m water muon veto, resulting in a detector system capable of achieving background-free operation in a 0.1 ton-year exposure [4]. Relevant design parameters for the light detection are also listed in table 1.

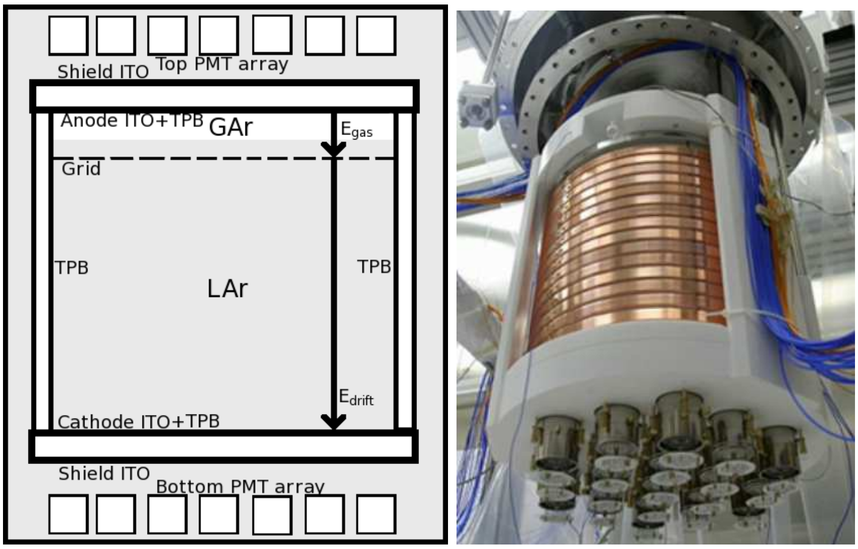

Figure 1. (Left) Conceptual drawing of the DarkSide two-phase liquid argon time projection chamber. See text and [3] for more details. (Right) The DarkSide-50 TPC assembled in the clean room at LNGS.

The third stage of the program is DarkSide-G2, a second generation detector with a 3.3 ton active mass of LAr reaching 10^{-47}cm^2 sensitivity level, is currently going into an R&D phase. The detector will be employed with the already existing neutron and muon veto.

2 LAr light detection in DarkSide

The rejection power achievable by pulse shape discrimination (PSD) is strongly affected by the amount of light detected. The experimental challenge for PSD comes from statistical fluctuations in the number of detected photons, which can wash out the difference between electronic and nuclear recoils for low energy events. Hence the overall LAr light detection efficiency sets the achievable energy threshold with the acceptable background leakage fraction and signal acceptance. The intrinsic scintillation light yield of LAr, a function of the type of interaction, energy deposited and applied electric field, defines the number of generated photons. The light collection efficiency (LCE) depends on the reflectivity of the TPC structure and LAr/GAr interface, the transparency of the electrodes used to set the electric field as well as the electronegative purity of LAr combined with the Rayleigh scattering length. The light detection efficiency (LDE) is determined by the overall LCE and the quantum efficiency (QE) of the photosensors. The measured light yield is then the combined function of the intrinsic light yield and the LDE. It is usually measured via γ-ray calibrations and expressed in terms of the number of detected photoelectrons (p.e.) per keV$_{ee}$ of “electron equivalent” energy deposited in LAr.

The default photosensors used in DarkSide are 3” Hamamatsu R11065 series PMTs with a QE of over 30%[5]. They are optimized for low temperature operation in LAr (87.8 K) and with the peak in the response function in the visible spectrum (λ ∼420 nm). In the DarkSide-10 runs at Princeton University, the bottom PMT array consisted of a single 8” Hamamatsu R5912-02 PMT with a QE of only 18%. Later it was replaced with an array of 3” R11065 PMTs.

The LAr scintillation light is peaked in the UV region at 128nm and as such would be effectively absorbed in the fused-silica windows of the PMTs. Therefore, the LAr scintillation light is wavelength shifted via tetraphenyl butadiene (TPB) films, whose peak emission wavelength is nicely matched to the peak of the PMTs response function. To achieve efficient photon conversion, TPB needs to be deposited on all surfaces which surround the TPC. The DarkSide program uses a novel approach in the TPC design with thin metal layers on two transparent windows instead of grids/meshes to define the horizontal boundaries of the TPC i.e. the anode and cathode electrode. The TPB can then be coated on the inner surfaces of the windows. The vertical boundaries (walls) of the TPC are defined by reflective material also coated by TPB (see figure 1). The TPB deposition is performed in-situ via thermal evaporation in a high-vacuum deposition system under a vacuum of $\sim$(2-7)$\times 10^{-8}$ Torr to ensure high quality of films. The TPB films are deposited with a thickness of about 200 μg/cm^2 for efficient UV-to-visible conversion efficiency and low absorption of the converted photons. The TPB coated surfaces are kept in an argon atmosphere but exposed to the ambient light.

The TPCs require electric fields in order to drift the ionization electrons and then extract and accelerate them in the GAr. This is achieved with a set of thin film electrodes, one grid and field cage shaping rings (outside the reflective housing). The anode and cathode electrodes in the form of thin Indium-Tin-Oxide (ITO) films are deposited on the inner surfaces of the same transparent windows, while the shielding electrodes for top and bottom PMT array are deposited on the outer surface of transparent windows. The ITO films are coated by an external company (ECI). The thickness of the films is set to the thinnest possible for the specific window material to minimize the absorption of the converted light that has to pass through at least two layers of ITO films to reach the PMTs. Materials used for the transparent windows are acrylic and later fused silica (Heraeus Suprasil 312). Both materials have a high transmission for visible light, are commonly used as a structural and window material and can be preselected for low radioactivity. However the minimal thickness of ITO layer on acrylic and fused silica discs recommended by the vendor were 100 nm and 15 nm, respectively. Hence the acrylic windows were replaced by fused silica windows to optimize light collection. The grid used to define the drift region (active volume) in LAr is a stainless steel grid etched with a hexagonal pattern. The absorption of UV photons depends on the grid thickness and pitch size. The anode window sits tightly on the TPC structure (diving bell) enabling the two-phase sensitive region and the PMTs to be completely immersed into LAr. The gas-liquid interface is maintained at the precise level between the grid and the anode window via heaters for gas argon production and a vent at the desired height.

The active volume of the TPC is contained within a cylindrical structure with 3M reflective foil (Vikuiti ESR) or high-reflectivity polytetrafluoroethylene (PTFE). Reflectivity measurements in the LAr surrounding, performed at Princeton University, indicate that 3M foil is a better reflector than 1/4” thick high-reflectivity PTFE [6]. However reflective foil cannot provide the mechanical support for the TPC so additional material is needed and care has to be taken to prevent any warping of the foil at low temperatures. Hence the decision was made to use a PTFE reflector until dedicated R&D tests related to foil mounting are completed. To enhance light collection, the space between the PMTs is filled/covered with 3M foil and/or PTFE reflectors.

The electro-negative impurities in LAr such as oxygen, nitrogen and water, can affect both the collection of the ionization electrons with characteristic electron lifetime (the time at which the

Table 1. Some parameters relevant for the light detection in DarkSide and the observed light yields in different runs of DarkSide-10 at the zero field using ^{22}Na γ-ray source with the vertical position at the TPC center. The optical transparency of the grids is estimated for normally incident light. The electron lifetime is obtained from gamma calibration runs with the electric (drift) field applied. The slow-component lifetime is estimated from the fit of the average scintillation waveforms from various γ-ray source runs at the zero field. More details can be found in [3].

Detector	**DarkSide-10**			**DarkSide-50**
Run	RunII at Princeton	RunIII at LNGS	RunIV at LNGS	Commissioning run
Run date	Dec 2010-Jan 2011	July-Dec 2011	Feb2012- Jan 2013	ongoing
Active LAr mass	$\sim$10 kg			$\sim$50 kg
Active Volume Size	ø 21 cm, d=23.5 cm			ø 40.6 cm, d=35.6 cm
Top PMT array	7× 3” R11065 $\langle$QE$\rangle$ $\sim$34%			19× 3” R11065 QE>30%
Bottom PMT array	8” R5912 QE$\sim$18%	7× 3” R11065 $\langle$QE$\rangle$ $\sim$34%		19× 3” R11065 QE>30%
TPB coating	$\sim$200μg/cm^2			
Windows	Acrylic 1/2” thick	Fused silica 1/2” thick		Fused silica 1/4” thick
Grid width/pitch/transparency	100μm/5mm/$\sim$89% at 90°			50μm/2mm/$\sim$95% at 90°
Gas pocket	2cm			1cm
ITO thickness	$\sim$ 100 nm	$\sim$15 nm		
Reflector	3M foil		PTFE 1/5” thick	PTFE 1” thick
GAr recirculation speed	$\sim$38kg/day			$\sim$75kg/day
Electron lifetime (E>0)	>200μs	$\sim$170μs		ongoing
Slow-component lifetime (E=0)	$\sim$1.6μs	(1.46-1.54)μs	$\sim$1.5μs	ongoing
Light yield (^{22}Na, E=0)	4.5p.e./keV$_{ee}$	(8.8-9.1)p.e./keV$_{ee}$	$\sim$7p.e./keV$_{ee}$	ongoing

total number of electrons produced is reduced by 1/e) and the light collection with the quenching in the slow-component amplitude, which also reduces the observed slow-component lifetime [7, 8]. During detector operation, LAr can be contaminated by the degassing process of the parts inside the detector. Hence it is necessary to ensure a continuous purification of GAr via a dedicated purifying unit (using SAES MonoTorr getters) with a recirculation speed as specified in table 1.

Table 1 summarizes the parameters listed above for different runs of DarkSide-10 as well as for DarkSide-50 together with the observed light yield at 511 keV$_{ee}$ and zero field operation. As it can be seen, the outcome of the detector optimization was a record light yield of 9.1 p.e./keV$_{ee}$ in the first underground run of DarkSide-10. Furthermore the observed light yields during the data taking runs were stable or increasing in agreement with the improvement of the LAr purity that is seen in the increase of the slow-component lifetime [3].

3 Summary

The high and stable scintillation light yield achieved in DarkSide-10 demonstrated excellent performance and validated the detector design with respect to the light detection and thus achievable energy threshold for PSD discrimination. The DarkSide-50 inner detector design was optimized based on experience with the prototype detector. The collaboration is currently commissioning the DarkSide-50 detector system, which is the first direct dark matter experiment to be operated inside an active neutron and muon veto. This system together, with innovative low background techniques, including naturally depleted argon, gives DarkSide-50 a unique capability of both measuring in-situ and rejecting various backgrounds.

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