WIMP Search with Underground Argon in DarkSide-50

Masayuki Wada for the DarkSide Collaboration
Princeton University, New Jersey, USA

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DarkSide-50 is a direct WIMP detection experiment at Gran Sasso underground laboratory in Italy based on a 50 kg dual-phase argon Time Projection Chamber with liquid argon from underground sources. DarkSide-50 aims to perform background-free WIMP searches with active vetos of a 30-tonne liquid scintillator neutron veto and a 1k-tonne water Cherenkov muon veto. DarkSide-50 has been taking data with underground Ar, which is significantly depleted in radioactive ^{39}Ar, and measured its depletion factor. The result of WIMP searches with 70 live-days of underground argon data will be presented. Also recent study of the liquid scintillator veto's performance and the future plan will be discussed.

1 Introduction

The ultimate goal of the DarkSide program is to detect signals from Weakly Interacting Massive Particles (WIMPs), one of the most popular dark matter candidates, by using liquid argon (LAr) as a target in a dual-phase Time Projection Chamber (TPC) with active background veto systems. In order to achieve the goal, the DarkSide program adopts various technologies to reduce and/or reject background events.

The main motivation to use LAr is its strong pulse shape discrimination (PSD) of electron recoils (ERs) from nuclear recoils (NRs), the expected signals from WIMP scatterings. The results from DarkSide-50 with atmospheric argon (AAr) data show that using PSD, a total of 1.5×10^7 ER events can be completely rejected in the WIMP energy region of interest, leaving no backgrounds (or WIMP signals) in the ROI after an exposure of (1422 ± 67) kg day [1]. Since LAr is relatively dense and easy to purify, it is scalable to large masses. Its high scintillation yield and good transparency to its own UV scintillation light lowers the detection threshold of the WIMP signal low and strengthens the PSD power. The high ionization and high electron mobility in LAr are suitable for TPC applications. It is very useful to remove surface background by fiducializing detection volume according to reconstructed 3D positions from ionization measurements. Furthermore, the ratio of ionization yield over scintillation yield provides additional discrimination power against ER backgrounds. A challenge of employing LAr as a target for WIMP detection comes from the high concentration of the beta-emitting isotope ^{39}Ar in atmospheric argon. Since ^{39}Ar has a decay half-life of 269 years and is mainly generated by cosmic rays in the atmosphere, underground argon sources (UAr) can be free of ^{39}Ar or have only trace amounts activated by radiation from the rock. A pioneering study of the ^{39}Ar activity in UAr was done and placed an upper limit on the ^{39}Ar depletion factor >150 relative to AAr [2]. In Sec. 3, we update this number with a measurement of the depletion factor

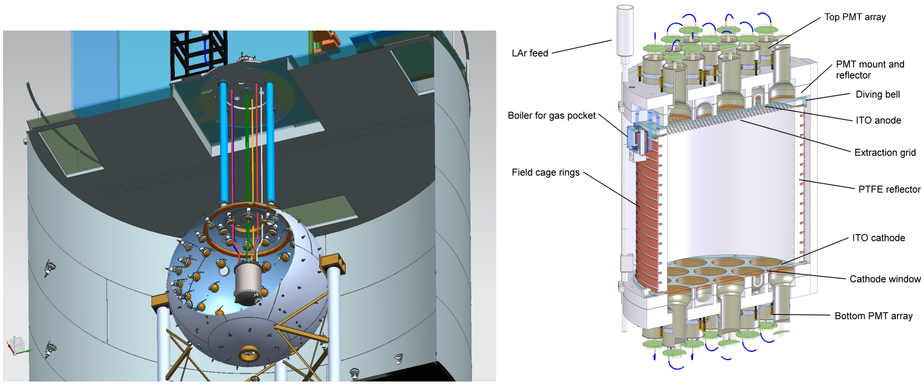

Figure 1: **Left:** The nested detector system of DarkSide-50. The outermost gray cylinder is the WCD, the sphere is the LSV, and the gray cylinder at the center of the sphere is the LAr TPC cryostat. The blue area at top is the radon-free clean room. **Right:** Schematic cross section of the DarkSide-50 Liquid Argon Time Projection Chamber

of ^{39}Ar in the DarkSide-50 detector. The strong PSD and depleted Ar coupled with scalability make LAr a viable target for sensitive WIMP detectors. The plans for a future liquid argon TPC are discussed in Sec. 4.

2 DarkSide-50 Detectors

DarkSide-50 consists of three nested detectors as shown in Fig. 1: the two-phase argon TPC, which is the main detector with a LAr target for WIMP detection; the organic Liquid Scintillator Veto (LSV), providing rejection against neutron and electron recoil backgrounds via anti-coincident signals from radiogenic and cosmogenic neutrons, γ's from the detectors, and cosmic muons; and the Water Cherenkov Detector (WCD), which rejects cosmic muons and suppresses radiogenic background from surrounding rocks and detectors.

Incoming WIMPs recoil from an Ar nucleus and leave excitations and ionizations, which the TPC measures by detecting scintillated photons with 19 PMTs each on top and bottom of the TPC. The excited Ar dimers de-excite and emit the first scintillation light, S1, at the vertex of the recoil. The ionization electrons drift due to an electric field of 200 V/cm, and are extracted into the gas phase at top of the TPC, generating the second scintillation light, S2. The time difference between S1 and S2 gives the depth (z position) of the event, and the transverse (x,y) position is reconstructed from the distribution pattern of S2 light among the top PMTs. The LSV has an array of 100 8" PMTs attached on the inside of a 4 m diameter stainless steel sphere filled with 30 tonne of liquid scintillator. The scintillator is a mixture of pseudocumene (PC) and trimethyl borate (TMB) with a wavelength shifter, Diphenyloxazole (PPO). Neutrons are detected in LSV via thermalization signals and/or capture signals, mainly on ^{10}B in the TMB. The veto efficiency of NRs from only capture signals are studied and estimated to be >99.1 % using an AmBe neutron source and MC simulation [3]. The study of the veto efficiency using thermalization signals is in progress using an AmC source, from which there is no coincident γ-rays produced with the neutrons.The WCD has an array of 80 8" PMTs mounted on the

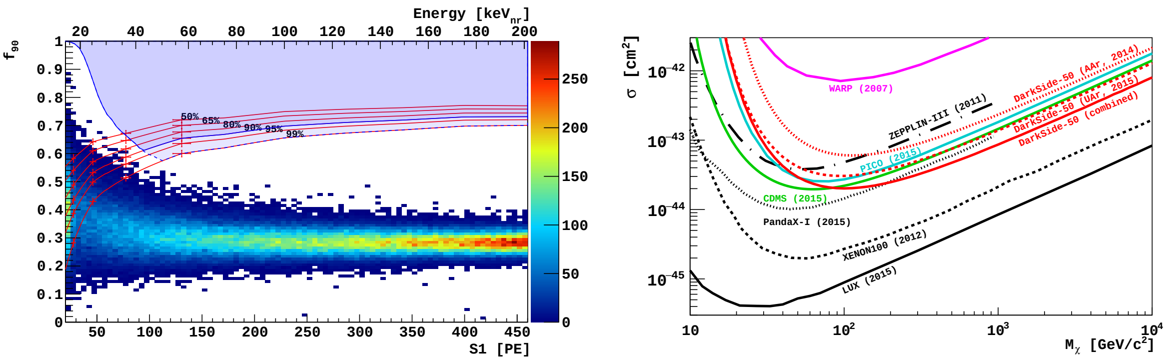

Figure 2: **Left:** Distribution of events in the f90 vs S1 plane surviving all cuts in the energy region of interest. Shaded blue with solid blue outline: WIMP search region. The f90 acceptance contours are drawn by connecting the red points derived from the SCENE measurements [6] and extending the contours using DarkSide-50 AmBe data. **Right:** Spin-independent WIMP-nucleon cross section 90 % C.L. exclusion plots for the DarkSide-50 AAr (dotted red) and UAr campaigns (dashed red), and combination of the UAr and AAr [1] campaigns (solid red).

inside of an 11 m diameter by 10 m high cylindrical tank filled with 1 k tonne of high purity water. Additional important parts of the DarkSide-50 experiment are radon-suppressed rooms with Rn-levels of 5 mBq/m^3, which is significantly less than typical Rn-levels in the air of $\sim$30 Bq/m^3. One of them is located directly on top of the WCD and provides a radon-free way to access the LSV and the TPC.

3 WIMP Search with an Underground Ar Target

The underground argon was extracted from a stream of gas from a CO_2 well in Cortez, Colorado, along with other gases including N_2 and He. This gas mixture was sent to Fermilab for further purification [4]. The purified UAr of (153 ± 1) kg was finally commissioned into the DarkSide-50 TPC at LNGS in Italy on April 1, 2015. In order to determine the ^{39}Ar depletion factor, a GEANT4-based MC simulation is used. The MC is tuned on the high statistic AAr data and validated against several γ calibration sources. The MC includes models of all three detectors and accounts for material properties, the photon propagation, and a model of LAr scintillation and ionization recombination. The ^{39}Ar activity is measured from a simultaneous MC fit to the S1 spectra of the field-off data and field-on (200 V/cm) data and the z-position distribution of events, which provides additional constraints on the rate of γ's from PMTs concentrated on the top and bottom of the TPC. The fit result gives an ^{39}Ar depletion factor of $(1.4 \pm 0.2) \times 10^3$ relative to AAr.

The WIMP search results with UAr [5] were based on the data set acquired from April 8 to July 31 in 2015 (70.9 live-days after data quality cuts) at a drift field of 200 V/cm. The light yield of S1 signals was determined to be (8.1 ± 0.2) PE/keV at zero field from the ^{83m}Kr peak, which is consistent with the light yield in AAr. Due to the purification at Fermilab and getter systems in DarkSide-50, we achieved a long electron lifetime of >5 ms, which is a measure of electronegative impurities, immediately after the UAr commissioning and it remains throughout the campaign. A set of criteria are used to select only possible WIMP recoils, i.e. single NRs in the fiducial volume, are described in detail in Ref. [5]. The events with coincident signals in the LSV or the WCD are also removed. The PSD parameter used in this analysis is f_{90}, the fraction of S1 light detected in the first 90 ns of the pulse. The WIMP region of interest (ROI) is defined in the f_{90} vs S1 space with a 90 % NR acceptance contour derived from the f_{90} response in SCENE [6], and a leakage curve corresponding to a total predicted leakage of <0.1 events during the exposure. The final event distribution in the f_{90} vs S1 space is presented in Fig. 2, and there are no events in the WIMP ROI. Given the background-free null result, a 90 % C.L. exclusion curve is drawn in Fig. 2. The combined result with AAr [1] puts an upper limit of $2.0 \times 10^{-44}\text{cm}^2$ on the WIMP-nucleon cross section at 100 GeV/c^2 WIMP mass.

4 DarkSide-20k

While DarkSide-50 continues the WIMP search with UAr and further investigates possible backgrounds, the DarkSide collaboration is moving to a next-generation detector. Given the exceptional PSD power of LAr and high depletion factor of UAr, we propose to build DarkSide-20k, a direct WIMP search detector using a LAR TPC with an active (fiducial) mass of 23 tonne (20 tonne) of depleted argon (DAr). In order to suppress both NR and ER backgrounds from conventional PMTs and improve light yield, silicon photomultipliers (SiPMs) are plan to be used and under development. To acquire the required amount of DAr with a sufficient depletion factor, two key projects are planned: Urania is an enlarged argon extraction plant in Cortez, Colorado, with expected capacity of 100 kg/day of UAr and Aria consists of two 350 m tall distillation columns, which are capable of depleting ^{39}Ar in UAr further with additional depletion factor between 10 to 100. DarkSide-20k aims for a 100 t yr exposure to give a projected sensitivity of $1.2 \times 10^{-47}\text{cm}^2$ for WIMP mass of 1TeV/c^2.

5 Conclusion

The DarkSide-50 detector achieved the most sensitive limit on WIMP-nucleon cross section among experiments using LAr. The ^{39}Ar depletion factor in UAr was determined to be $(1.4 \pm 0.2) \times 10^3$ relative to AAr. DarkSide-20k is forthcoming.

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