The DarkSide awakens

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Abstract.
The DarkSide program at LNGS aims to perform background-free WIMP searches using two phase liquid argon time projection chambers, with the ultimate goal of covering all parameters down to the so-called neutrino floor. One of the distinct features of the program is the use of underground argon with has a reduced content of the radioactive ^{39}Ar compared to atmospheric argon. The DarkSide Collaboration is currently operating the DarkSide-50 experiment, the first

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such WIMP detector using underground argon. Operations with underground argon indicate a suppression of ^{39}Ar by a factor $(1.4 \pm 0.2) \times 10^3$ relative to atmospheric argon. The new results obtained with DarkSide-50 and the plans for the next steps of the DarkSide program, the 20 t fiducial mass DarkSide-20k detector and the 200 t fiducial Argo, are reviewed in this proceedings.

1. Introduction
The DarkSide project at Laboratori Nazionali del Gran Sasso (LNGS) aims to perform background-free WIMP searches using two phase liquid argon time projection chambers (LAr TPCs). One of the advantages of argon is the powerful pulse-shape discrimination (PSD) between electron recoils (such as β and γ decays) and nuclear recoils (such as an elastic scattering interaction between a WIMP and a nucleus). One of the distinctive features of the program is the use of underground argon (UAr), which has a lower content of the radioactive ^{39}Ar compared to atmospheric argon (AAr).

2. Updates on DarkSide-50
2.1. Detector description
The DarkSide-50 detector system is described in Ref. [1, 2] and in several proceedings of the collaboration. The apparatus consists of three nested detectors. Innermost is the cylindrical LAr TPC, with an active UAr mass of (46.4 ± 0.7) kg observed by 38 3" PMTs. The design of the DarkSide-50 TPC is based upon the successful prototype DarkSide-10 [3]. The LAr TPC is mounted and operated at the center of a liquid scintillator veto (LSV), described in Ref. [4], consisting of a 4.0 m diameter stainless steel sphere instrumented with 110 PMTs and filled with 30 tonnes of boron-loaded liquid scintillator. The scintillator is a solution of pseudocumene (PC), with 5 % by volume trimethylborate (TMB). Surrounding the LSV is a 1 kt water Cerenkov veto (WCV) instrumented with 80 PMTs to veto the residual cosmic-ray muons present at the LNGS depth [5]. Signals from the LSV and WCV are used to reject events in the LAr TPC caused by cosmogenic neutrons [6, 7] or by neutrons and γ-rays from radioactive contamination in the detector components.

An interaction in the LAr target generates primary scintillation light (S1 pulse) and ionization electrons. The electrons escaping recombination drift in the TPC electric field to the surface of the LAr, where a stronger electric field extracts them into the gaseous region, where they induce further light emission (S2 pulse) via proportional scintillation. The S1 and S2 signals together allow the interaction vertex to be localized in 3D. LAr TPC technology allows rejection of backgrounds from γ-ray- and β-decay-induced events by using PSD. The PSD parameter used in the WIMP searches is f_{90}, the fraction of S1 light in the first 90 ns of the scintillation pulse.

2.2. Run with atmospheric argon
A first run of DarkSide-50, with data taken during 2014 with a (1422 ± 67) kg d exposure of AAr, produced a null result for the WIMP search with zero backgrounds from ^{39}Ar decays [1]. A total of 1.5×10^7 events in the LAr TPC, mostly originating from ^{39}Ar, were collected. All but two of the events falling within the WIMP region of interest were rejected using the PSD. The two remaining events in the WIMP search region had a signal in coincidence with the LSV and were therefore discarded.

2.3. Detector calibrations
The DarkSide-50 detectors have been calibrated *in situ* during 2014 and 2015, using a series of γ and neutron radioactive sources placed inside the LSV next to the TPC. Data taken with

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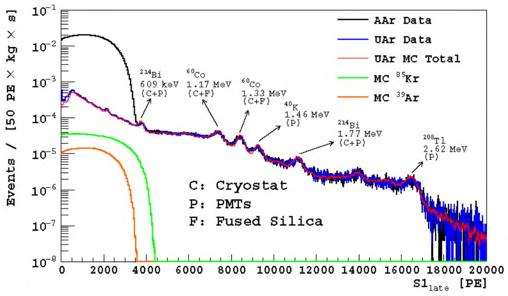

Figure 1. Live-time-normalized S1 pulse integral spectra obtained at zero drift field, with an AAr fill (black) and a UAr fill (blue). Also shown are the fit to the UAr data (red) and individual components of ^{85}Kr (green) and ^{39}Ar (orange) extracted from the fit. See Ref. [2] for a detailed description.

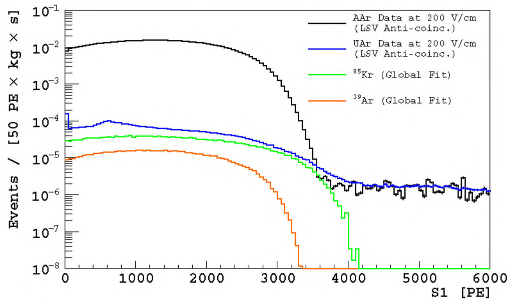

Figure 2. Live-time normalized S1 pulse integral spectra from single-scatter events in AAr (black) and UAr (blue) taken with 200 V/cm drift field. Also shown are the ^{85}Kr (green) and ^{39}Ar (orange) levels as inferred from a spectral fit. See Ref. [2] for a detailed description.

^{57}Co, ^{133}Ba, and ^{137}Cs γ-ray sources were used to validate Monte Carlo (MC) simulations, and data taken with AmBe neutron sources were used to validate the transfer of the nuclear recoil response from SCENE [8] to DarkSide-50, as described in Ref. [2].

The calibration with AmBe neutron sources allowed for the measurement of the LSV response to neutron captures, which occurs predominantly on ^{10}B and ^{1}H, with estimated probabilities for the current TMB concentration of ∼92 % and ∼8 %, respectively. Neutron capture on ^{10}B in the TMB can occur through two channels [9]:

$$
\begin{aligned}
{}^{10}\mathrm{B} + n &\rightarrow \alpha\,(1775\,\mathrm{keV}) + {}^{7}\mathrm{Li} && (\mathrm{BR}{:}\,6.4\,\%)\\
{}^{10}\mathrm{B} + n &\rightarrow \alpha\,(1471\,\mathrm{keV}) + {}^{7}\mathrm{Li}^{*} && (\mathrm{BR}{:}\,93.6\,\%)\\
{}^{7}\mathrm{Li}^{*} &\rightarrow {}^{7}\mathrm{Li} + \gamma\,(478\,\mathrm{keV})
\end{aligned}
$$

The scintillation light resulting from the α and ^{7}Li of the ground state channel is quenched to 25 to 35 PE, while the 478 keV γ-ray accompanying the $^{7}\mathrm{Li}^{*}$ channel gives 240 PE when the γ-ray is fully absorbed. These signals are both well above the LSV analysis threshold of a few PE [4].

2.4. Underground argon

After the AAr run, the TPC was drained and filled with low radioactivity UAr in April 2015. The low radioactivity UAr was extracted from the Doe Canyon CO_2 wells. It was transported to Fermilab where it was purified to < 10 ppm of CO_2, N_2, O_2, and He. A total of 155 kg of low radioactivity UAr has been obtained. The purified UAr was sent to LNGS for final gettering to detector-grade argon [10, 11].

Fig. 1 compares the measured zero-field spectra for the UAr and AAr targets. The background γ-ray lines originate from identified levels of ^{238}U, ^{232}Th, ^{40}K, and ^{60}Co in the detector construction materials, and are consistent with the expectations from materials screening. The positions of the γ-ray peaks in the AAr and UAr spectra are the same.

An unexpected contamination of ^{85}Kr is present in the UAr spectrum, which was not seen in that of the AAr. This is evident in Fig. 2, which compares the UAr and AAr spectra for the S1 pulse, with a 200 V/cm drift field. The ^{39}Ar activity of (0.73 ± 0.11) mBq/kg and ^{85}Kr activity of (2.05 ± 0.13) mBq/kg in the UAr are determined by a combined fit to the spectra of S1-late with field off (Fig. 1), S1 with field on (Fig. 2) and the z-position distribution. The ^{39}Ar activity of the UAr corresponds to a depletion by a factor of $(1.4 \pm 0.2) \times 10^{3}$ relative to AAr [2].

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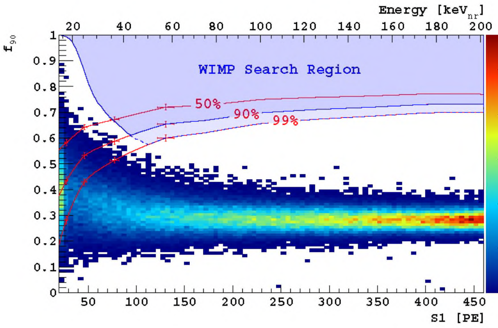

Figure 3. Distribution of events in the f_{90} vs S1 plane which survive all physics cuts. Shaded blue with solid blue outline: WIMP search region. See Ref. [2] for a detailed description.

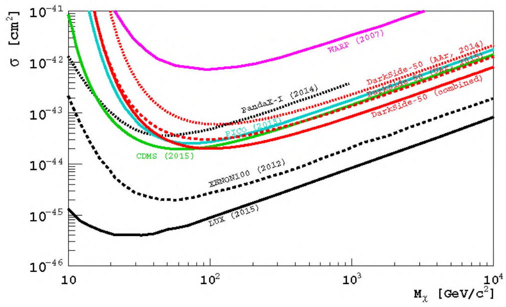

Figure 4. Spin-independent WIMP-nucleon cross section 90 % C.L. exclusion plot for DarkSide-50, compared to other experiments. See Ref. [2] for a detailed description and references.

An independent estimate of the ^{85}Kr decay rate is obtained by measuring its 0.43 % decay branch to metastable $^{85\mathrm{m}}$Rb, which gives a γ-ray with mean lifetime of 1.46 µs following the β-decay. The measurement of the decay rate of ^{85}Kr via $^{85\mathrm{m}}$Rb gives (33.1 ± 0.9) events/d, in agreement with the value (35.3 ± 2.2) events/d obtained from the known branching ratio and the spectral fit result. The presence of ^{85}Kr in UAr was unexpected, and so no attempts were made to remove it from the UAr, which could have been done via cryogenic distillation. The ^{85}Kr in UAr could come from atmospheric leaks or from deep underground natural fission processes [1].

2.5. WIMP search with low radioactivity underground argon

The first WIMP search in DarkSide-50 using UAr has been reported in Ref. [2], where it is shown that the combination of the electron recoil background rejection observed in the AAr run, and the reduction of ^{39}Ar from the use of UAr would allow DarkSide-50 to be free from ^{39}Ar background for several tens of years.

A non-blind physics analysis was performed. The TPC and veto physics cuts applied, as well as their efficiency and acceptance, are described in Ref. [2, 4]. The distribution of events in the f_{90} vs. S1 plane, after all quality and physics cuts, is shown in the left panel of Fig. 3. There are 1.26×10^5 events in the energy region of interest, defined as 20 PE to 460 PE (13 keV$_{\mathrm{nr}}$ to 201 keV$_{\mathrm{nr}}$). The WIMP search region, shown in Fig. 3, is defined as a region in the f_{90} vs. S1 plane with known high acceptance for nuclear recoils and low leakage of single-scatter ER events, as described in Ref. [2].

No events are present within the WIMP search region. Dark matter limits from the present exposure are determined from our WIMP search region using the standard isothermal galactic WIMP halo parameters. When combined with the null result of the previous AAr exposure in DarkSide-50, a 90 % C.L. upper limit on the WIMP-nucleon spin-independent cross section of 2.0×10^{-44} cm^2 (8.6×10^{-44} cm^2, 8.0×10^{-43} cm^2) for a WIMP mass of 100 GeV/c^2 (1 TeV/c^2, 10 TeV/c^2) is obtained. Fig. 4 compares these limits to those obtained by other experiments. A detailed description can be found in Ref. [2].

3. The future steps of the DarkSide program

3.1. DarkSide-20k and Argo

The combination of the AAr and UAr results in DarkSide-50 leads to the expectation that a background-free result can also be obtained from a much larger exposure with a multi-tonne detector. On this basis, an enlarged DarkSide Collaboration has proposed the construction of DarkSide-20k, a direct WIMP search using a LAr TPC with an active (fiducial) mass of 23 t (20 t) of depleted argon (DAr). DAr is UAr which has been further depleted in ^{39}Ar by means of

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isotopic separation. DarkSide-20k is designed to achieve a background-free exposure of 100 t yr accumulated during a run of 5 years, giving a sensitivity to WIMP-nucleon interaction cross sections of $1 \times 10^{-47}\,\mathrm{cm}^2 (1 \times 10^{-46}\,\mathrm{cm}^2)$ for WIMPs of $1\,\mathrm{TeV/c}^2$ ($10\,\mathrm{TeV/c}^2$) mass.

In the longer term, the aim of the DarkSide collaboration is to develop a path towards a WIMP detector to be built and operated at LNGS with a 300 t (200 t) DAr target (fiducial) mass. For now, this ultimate experiment is called Argo. Argo is planned to accumulate an exposure of 1000 t yr, free of backgrounds other than those induced by coherent scattering of neutrinos, and thus be sensitive to WIMP cross sections below the neutrino floor.

3.2. Urania and Aria
Procurement of the necessary quantity of low radioactivity UAr for DarkSide-20k is the critical technical challenge for the experiment, and will be addressed within the framework of the Urania and Aria projects. The Urania project will provide a plant capable of extracting 100 kg/d of UAr from the same wells that yielded the UAr for DarkSide-50. The Aria project will provide a cryogenic distillation plant capable of reducing the residual ^{39}Ar in the UAr by a factor of 10 per pass, at a rate of 150 kg/d, by exploiting the small difference in vapor pressure between ^{39}Ar and ^{40}Ar. The Urania and Aria projects will ultimately supply the DAr for the DarkSide-20k experiment.

4. Conclusions and Outlook
The DarkSide collaboration reported the first WIMP search using low radioactivity UAr [2], resulting in the best WIMP limits obtained with argon. The combination of PSD in argon and low radioactivity UAr lead to the expectation that a background-free result can also be obtained with a multi-tonne detector. The DarkSide collaboration has proposed the construction of the 20 t fiducial mass DarkSide-20k detector.

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