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DarkSide-50: a WIMP search with a two-phase argon TPC

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Abstract

DarkSide-50 is a two phase argon TPC for direct dark matter detection which is installed at the Gran Sasso underground laboratory, Italy. DarkSide-50 has a 50-kg active volume and will make use of underground argon low in ^{39}Ar. The TPC is installed inside an active neutron veto made with boron-loaded high radiopurity liquid scintillator. The neutron veto is installed inside a 1000 m^3 water Cherenkov muon veto. The DarkSide-50 TPC and cryostat are assembled in two radon-free clean rooms to reduce radioactive contaminants. The overall design aims for a background free exposure after selection cuts are applied. The expected sensitivity for WIMP-nucleon cross section is of the order of 10^{-45} cm^2 for WIMP masses around 100 GeV/c^2. The commissioning and performance of the detector are described. Details of the low-radioactivity underground argon and other unique features of the projects are reported.

Selection and peer review is the responsibility of the Conference lead organizers, Frank Avignone, University of South Carolina, and Wick Haxton, University of California, Berkeley, and Lawrence Berkeley Laboratory

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1. The DarkSide Program

The DarkSide collaboration, consisting of 28 university and national-laboratory groups from seven countries, is embarked on a program of direct searches for dark matter in the form of weakly-interacting massive particles (WIMPs) using two-phase argon time projection chambers (TPCs). The program is based in the Gran Sasso National Laboratory (LNGS) in Italy. As currently envisioned, the program consists of the detectors shown in Fig. 1: a 10-kg prototype, the 50-kg experiment discussed here, and a proposed "Generation 2" multi-ton experiment.

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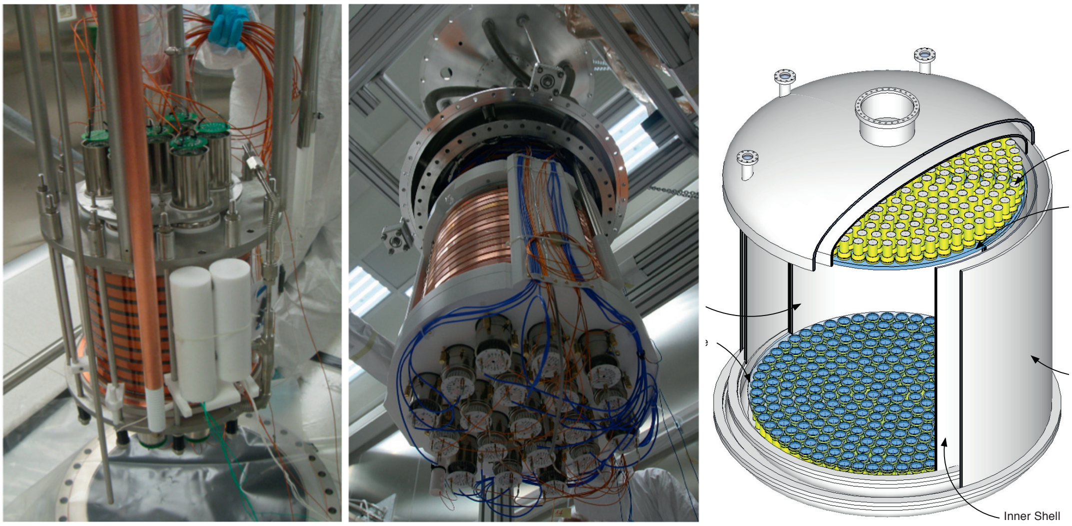

Fig. 1. **Left:** the DS-10 prototype, with 10 kg of active argon, which ran in Princeton for 200 days and at LNGS for 500 days. **Center:** the DS-50 TPC, 50 kg active/33 kg fiducial, now in operation at LNGS, with an expected sensitivity for the WIMP-nucleon cross section of about 10^{-45} cm^2 in a three-year run. **Right:** the DS-G2 TPC, 3.3 T/2.8 T active/fiducial, sensitivity about 10^{-47} cm^2 in a five-year run.

The DarkSide-50 TPC (Fig. 1-center) has an active volume of liquid argon 35.6 cm in diameter and height viewed by 19 Hamamatsu R11065 3-inch, low-background, high-efficiency PMTs. A fused silica "diving bell" contains a 1-cm-high gas pocket for measuring ionization via secondary scintillation. Indium-Tin-Oxide electrodes on the diving bell and cathode window, a set of copper rings, and an etched stainless steel grid provide the drift, extraction, and electroluminesent fields to collect and amplify the ionization electrons.

2. Background rejection in DarkSide

We are seeking evidence for WIMPs by their (rare) interactions with the liquid argon target. The strongest expected channel is the coherent elastic scattering from the argon nuclei. The signature is thus a "nuclear recoil", the low-energy but detectable motion of an argon atom in the liquid argon. A design goal of the DarkSide program is to develop detectors that can sustain multi-year, background-free runs. The main backgrounds to contend with are:

- Electromagnetic backgrounds. These are either interactions of γ-rays giving recoiling electrons via Compton scattering or photoelectric absorption or electrons from β decay. In argon, the dominant source of electrons is the β decay of ^{39}Ar, which is present in atmospheric argon at a level of 1 Bq/kg.
- Neutron interactions. The neutrons can be cosmogenic or radiogenic. The worst of the latter are from (α, n) interactions in the materials of the detector itself, and in most detectors, DarkSide included, the largest source is the photomultiplier tubes (PMTs). Neutrons give nuclear recoils that are indistinguishable from those of WIMPs.
- Surface backgrounds. The worst of these occur when an α decay has the α go deeper into the surface and the recoiling daughter nucleus is emitted into the liquid argon, mimicking the signal.

The DarkSide detectors are located in Hall C of LNGS, with a 3400 meter-water-equivalent overburden. This reduces the flux of cosmic ray muons by a factor of 10^6, reducing cosmogenic neutrons as well. The DarkSide-50 TPC is installed in a 4-m-diameter tank (see Fig. 2) containing borated liquid scintillator and

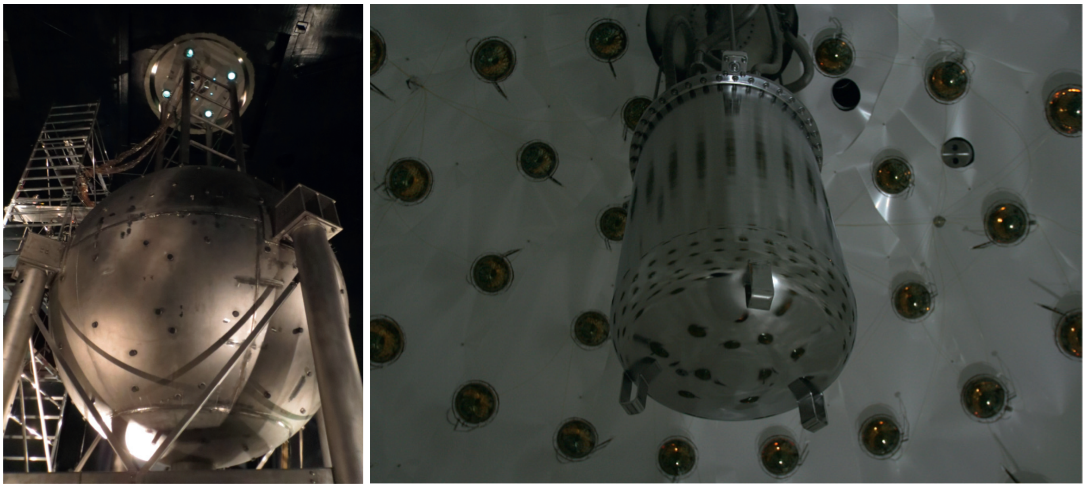

Fig. 2. **Left:** the borated-liquid-scintillator neutron veto. **Right:** the DS-50 TPC cryostat in the neutron veto.

Fig. 3. **Left:** the water Cherenkov muon veto (blue tank) and assembly/installation cleanroom (silver box). **Right:** the parts-preparation cleanroom.

instrumented with 110 8-inch PMTs to act as a neutron veto. The neutron veto is itself installed in an 11-m-diameter × 10-m-high tank of ultra-pure water, instrumented with 80 8-inch PMTs that serves both as shielding and a Cherenkov detector of the residual muons (see Fig. 3-left). These facilities are all sized for DarkSide-G2.

Together, these detectors reduce the backgrounds from cosmogenic and external radiogenic backgrounds to negligible levels. With the dominant backgrounds coming from the TPC itself, every effort is made to use materials that are radio-pure. We have chosen the materials by an elaborate program of screening using gamma counting, GDMS, and other techniques. With the powerful electromagnetic background rejection available in liquid argon (see below), we pay particular attention to radiogenic neutron production.

The largest source of electromagnetic background is the argon target itself. The DarkSide TPCs will use argon from underground sources. Using a low-background liquid argon scintillation counter, we have measured this argon to contain less that 1/150 times the ^{39}Ar concentration of atmospheric argon [1], as shown in Fig. 4.

The remaining electromagnetic backgrounds will be handled by pulse shape discrimination (PSD) of the liquid argon scintillation [2], a particular strength of liquid argon. In liquid argon, the scintillation light has two components, with decay times of ~7 ns and ~1.5 μs, respectively. Due to differences in ionization

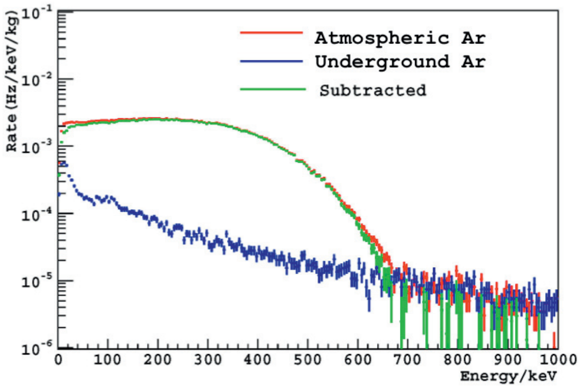

Fig. 4. The energy spectrum of events in atmospheric argon (red) and argon from underground (blue). The difference (green) shows the shape of the ^{39}Ar β-decay spectrum. There is no evidence of ^{39}Ar in the underground argon, and Ref. [1] sets an upper limit of 0.0065 Bq/kg, a factor of 150 lower than atmospheric argon.

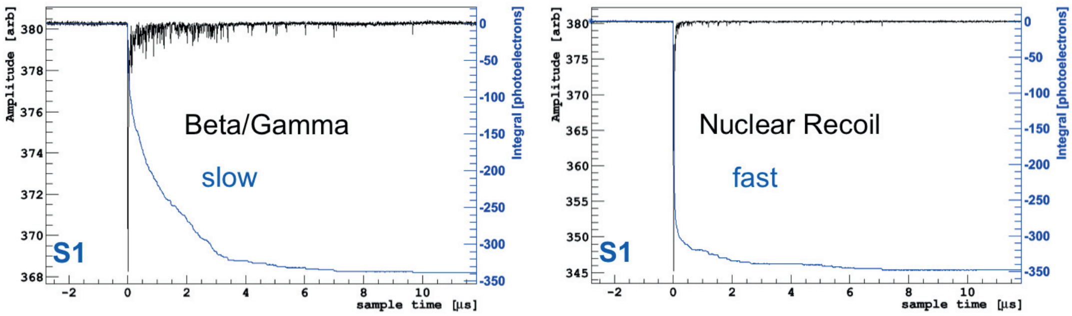

Fig. 5. Pulse shape discrimination in liquid argon. Digitized scintillation pulses from DarkSide-10 for an electron recoil (left) in a run with a gamma source and from a nuclear recoil (right) from a run with an Am-Be neutron source. The two pulses were chosen to have the same amount of integrated scintillation light (blue scale on right).

density, electrons and nuclear recoils populate the two components very differently, with the electron light being primarily slow, and the nuclear recoil light primarily fast. This is illustrated with DarkSide-10 data in Fig. 5.

A two-phase TPC also measures ionization by drifting electrons to the liquid surface, extracting them into the argon gas above, and accelerating them, producing a secondary-scintillation signal, S2. (The primary scintillation in the liquid is called S1.) The drift time (the time between S1 and S2) measures the vertical position of the event in the liquid argon, while the pattern of S2 light in the top PMT array determines the horizontal position. Further, the ratio S2/S1 is a second source of electromagnetic background rejection. This rejection is approximately independent of the PSD, as shown in Fig. 6.

Our simulations based on measured radioactivity of detector components indicate that the dominant sources of neutron background are the PMTs, followed by the cryostat. Our rejection of neutron-induced events is based on detecting the multiple interactions expected from neutrons. The strategy is shown in Fig. 7 which diagrams the interactions of several neutrons emitted from the PMTs. From left to right in the figure: nuclear recoils in the active volume of the TPC an be identified as neutron-induced by looking for multiple interactions in the TPC, a signal from a neutron capture in the surrounding neutron veto, or the detection in either the TPC or neutron veto of a γ ray from neutron capture in inactive material. Our simulations indicate that the rejection of neutron-induced nuclear recoils in the TPC by the neutron veto should exceed 100.

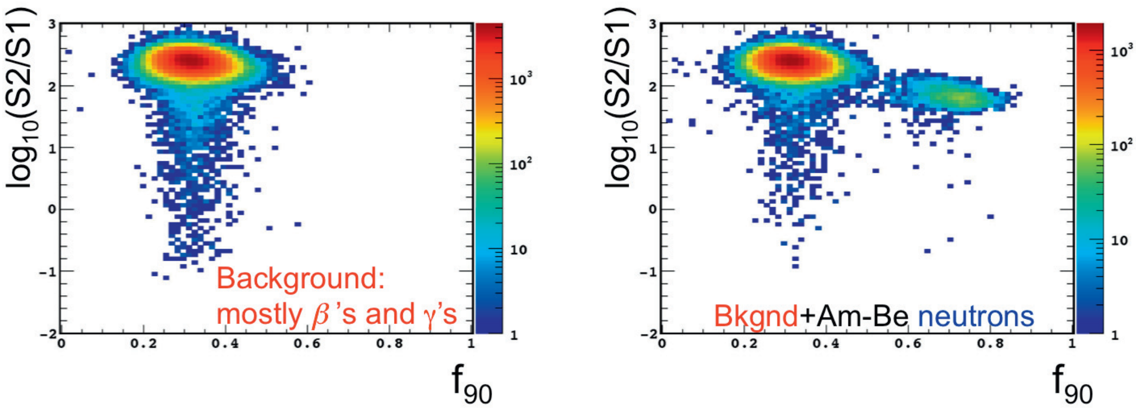

Fig. 6. Combined electromagnetic background discrimination in liquid argon. The ratio of ionization to scintillation (S2/S1) is plotted vs. the PSD parameter f90, the fraction of primary scintillation in the first 90 ns. DarkSide-10 data taken with a gamma source (left) and with an Am-Be neutron source (right). The events are selected to have 100-200 S1 photoelectrons, corresponding to ≈57-114 keV$_r$ in DS-10 and somewhat lower energies in DS-50.

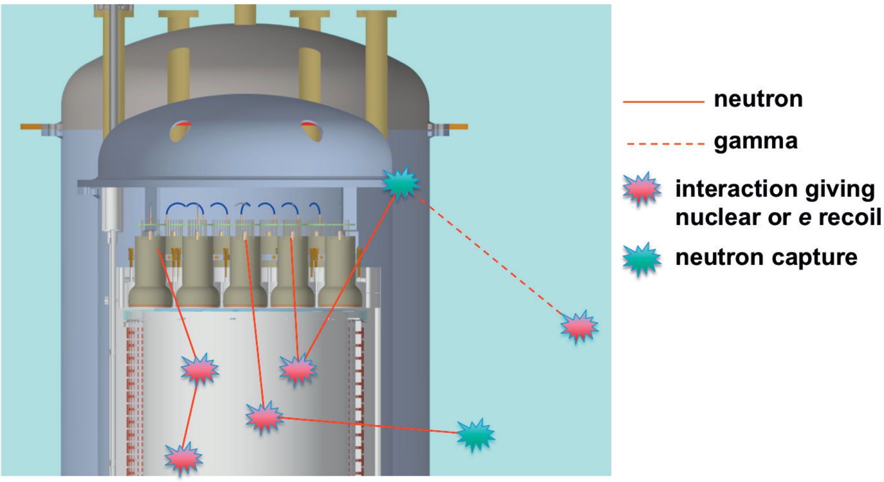

Fig. 7. Various neutron-induced background processes and their rejection.

We control surface background initially by limiting exposure of surfaces to radon and its daughters. All parts are cleaned and prepared for assembly in one of our radon-suppressed cleanrooms. This includes the application of the TPB wavelength shifter needed to convert the 128-nm argon emission to the visible. The parts are transferred in radon-proof containers to the assembly/installation cleanroom on top of the water tank. Both cleanrooms are supplied with air that that has been scrubbed of radon, with residual levels in the work areas of 5-50 mBq/m^3. From the cleaning until the cryostat and cable ducts are sealed, the TPC is exposed only to radon-scrubbed air. The final rejection of surface background is the fiducialization made possible by the 3-dimensional position reconstruction of the TPC.

3. DarkSide-50 status (as of September 8, 2013) and prospects

In Spring 2013, a trial assembly of the TPC was performed, and it was installed in the (air-filled) vetoes for a test run. The TPC was instrumented with about half of the R11065-20 PMTs that were to be used

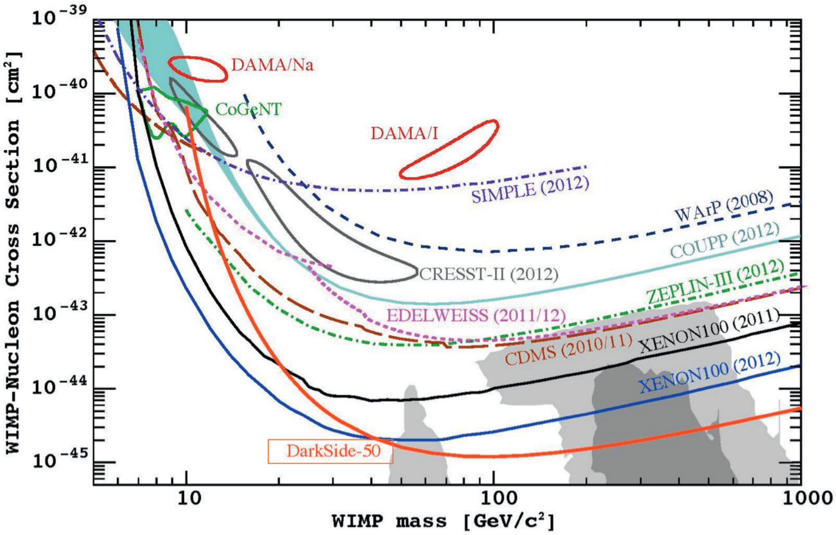

Fig. 8. Estimated sensitivity of DarkSide-50 with a 0.1 ton-year exposure.

in the physics run, with the arrays filled out with older R11065s. A major finding of the test run was that the R11065-20s did not work at liquid argon temperatures. This issue is now being resolved by intense collaboration between DarkSide and Hamamatsu, but it meant we had to deploy DarkSide-50 for the physics run with the higher-radioactivity R11065s. (Update: all 38 R11065s have been running well since they were turned on right after TAUP.) The test run also proved that the cooling and recirculation/purification system worked well, with an observed electron drift lifetime of >3 ms, to be compared to a maximum electron drift time of about 500 μs. The TPC high voltage system did not quite reach its design maximum voltage, but operated stably at twice the optimal voltage to be used in the physics run.

The TPC was reassembled with working PMTs in August-September 2013 and installed in the vetoes. As of TAUP 2013, the next steps were to fill the TPC with atmospheric argon, commission the TPC, then fill the vetoes and commission them, which was accomplished by mid-November. The first physics run was a background run with atmospheric argon. This run will give an ^{39}Ar statistics greater than the planned 3-year run with underground argon and would thus be a thorough test of the PSD rejection. This run is nearing completion (March, 2014). When this and other calibration running are complete in Summer 2014, the TPC will be emptied (in place) and refilled with underground argon for the main WIMP search.

Our background calculations assuming the use of R11065-20s indicated that there would be <0.1 event of neutron background in the proposed 3-year (0.1 ton-year) exposure. With R11065s, the background is still predicted to be well under 1 event. A model for the PSD based on DarkSide-10 data and cuts tuned to give 0.1 event of ^{39}Ar background give an acceptance that turns on at 20 keV$_r$ and reaches 50% (100%) at ~40 (~70) keV$_r$. This gives the sensitivity curve shown in Fig. 8.

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[2] M. G. Boulay, A. Hime, Technique for direct detection of weakly interacting massive particles using scintillation time discrimination in liquid argon, Astropart. Phys. 25 (2006) 179.