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Recent resuts from DARKSIDE

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Summary. — DARKSIDE is a multi-stage program devoted to the direct detection of Dark Matter particles with a double phase liquid Argon Time Projection Chamber. Presently the DARKSIDE-50 detector is running underground at the Laboratori Nazionali del Gran Sasso. It is placed inside a 30 t liquid organic scintillator sphere, acting as a neutron veto and hosted by a 10 kt water Cherenkov detector. The DARKSIDE-50 setup with TPC filled with atmospheric argon is operating since November 2013 and we report here the first results of a Dark Matter search for a (1422 ± 67) kg×d truly background-free exposure. It can be translated into a 90% C.L. upper limit on the WIMP-nucleon cross section of 6.1×10^{-44} cm^2, for a WIMP mass of 100 GeV/c^2, being up to date the strongest limit obtained with an argon target.

PACS 95.35.+d – Dark matter.
PACS 29.40.Mc – Scintillation detectors.
PACS 29.40.Gx – Tracking and position-sensitive detectors.

1. – Introduction

Our knowledge about the composition of the Universe is derived only by indirect observations. We know that the baryonic matter (luminous matter) accounts only for about 5%, while Dark Energy and Dark Matter (DM) are estimated to provide the larger contributions, which account for ∼68% and ∼27%, respectively (according to the recent results of the Planck experiment).

A leading candidate explanation is that DM is composed of Weakly Interacting Massive Particles (WIMPs) formed in the early Universe and gravitationally clustered together with the standard baryonic matter. WIMPs could have been thermally produced in the very early Universe and their expected masses are between 1 GeV/c^2 and 10 TeV/c^2. In order to convincingly detect a WIMP signal, a specific signature from a particle populating our galactic halo is important *i.e.* the Earth's motion through the galaxy induces a seasonal variation of the total event rate. The observation of a recoil spectrum with at least two different targets should provide complementary information on the WIMP properties, such as the WIMP mass. Once a WIMP signal is detected, isotopic separation in odd and even nuclei can further distinguish between spin-dependent and spin-independent interactions, using the same detector.

Experimental searches for WIMP candidates have been already conducted for many years. These efforts can be divided into two broad classes: direct detection [1], in which the Dark Matter particles are observed in a detector through elastic scattering of the nucleus of ordinary matter, and indirect detection [2], where one looks for the products of Dark Matter annihilations in their high density regions or in space. There are also attempts to combine data from both types of experiments in order to extract the DM parameters [3].

WIMPs appearing in terrestrial detectors would primarily be those gravitationally bound to our galaxy. Since the escape velocity is a few hundred km/s [4] one can easily estimate that the maximum energy transfer from a WIMP to an electron initially at rest is at most in the eV range, while the energy transfer to an atomic nucleus would typically be in the range of some tens of keV_r(1). Therefore direct detection experiments typically search for nuclear recoils. The cross section for WIMP-nucleon interaction calculated *i.e.* using minimal super-symmetric models (popular extensions of the Standard Model) spans many orders of magnitude. Typical values for the spin-independent cross section are between $10^{-44}\,cm^2$ and $10^{-46}\,cm^2$ [5,6]. Such small values imply that large target masses and long measurement times are required. At the lower end of the cross section range typical interaction rates are a few events per ton and per year. These low expected rates pose a major challenge considering that typical background rates from environmental radioactivity and cosmic radiation are much higher.

2. – The DARKSIDE program

The ultimate goal of the DARKSIDE project is to develop and deploy a background-free multi-ton liquid argon (LAr) detector that has best sensitivity for direct searches of WIMP interactions. LAr is a promising medium for WIMP detection due to its efficient conversion of energy from WIMP-induced nuclear recoils into both scintillation and ionization signals. In a Time Projection Chamber (TPC), scintillation (causing the so-called S1 signal) and ionization (S2) can be independently detected and spatially resolved through large volumes of liquid. The relative size and time dependence of these signals permit discrimination of nuclear recoils from background events (mostly gammas and electrons). LAr allows also for very effective pulse shape discrimination (PSD) of the S1 signal between different types of radiation, thus opens up possibilities for powerful background reduction.

In order to accomplish the ambitious goals, the DARKSIDE collaboration is proceeding through a staged approach. The first prototype with 10 kg of LAr (DARKSIDE-10), built at the Princeton University and run in the underground laboratory of the Laboratori Nazionali del Gran Sasso (LNGS Italy, overburden by 3400 m.w.e of rock working as a shield from cosmic rays) until 2013, proved the stability of the detector and showed possibilities to achieve a record light yield of 8.9 p.e./keV_{ee}(2) [7].

In the next step the DARKSIDE-50 detector with the active mass of about 50 kg has been completed. Its construction is based on several innovative features that allow for truly background-free operations, which results in a significant science result in spite of

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(1) keV_r refers to the nucleus recoil energy.
(2) keV_{ee}: electron recoil equivalent.

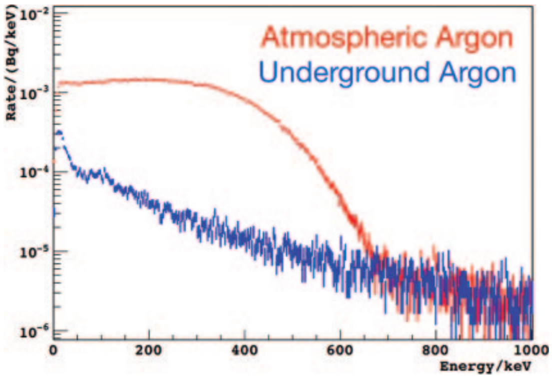

Fig. 1. – Spectra of the atmospheric (red) and the underground Argon (blue) measured at the KURF underground laboratory.

relatively small size of the detector. Development of the innovations described below is an important goal in its own right as they are part of the background reduction strategy followed by the DARKSIDE collaboration. DS-50 serves also as a prototype for a future multi-ton detector. The very unique features of DARKSIDE-50 are:

- Application of underground argon (UAr) depleted in the radioactive isotope ^{39}Ar. Atmospheric abundance of ^{39}Ar in Ar ($\sim$1 Bq/kg) limits the size of a DM detector based on LAr to some hundreds kilograms. In order to overcome this problem the DARKSIDE collaboration is planning to use Ar extracted from an underground source (^{39}Ar is produced in the atmosphere by cosmic ray interactions such as ^{40}Ar(n,2n)^{39}Ar) at the Kinder Morgan Doe Canyon CO_2 complex located in Cortez, Colorado, USA. A plant for the separation of depleted argon at this site has been deployed. It is fed with CO_2 gas coming from underground wells and containing argon at a concentration of $\sim$400 ppm, and produces a crude argon mixture containing argon with a typical concentration of $\sim$3% (with the balance of N_2 and He). Separation of the depleted Argon produced in the Cortez facility from the accompanying Nitrogen and Helium is accomplished by cryogenic distillation. The system is running at Fermilab delivering 99.9999%-purity argon. Up to now the collaboration has produced and purified 156.4 kg of UAr, what is sufficient to fill the DS-50 detector. Figure 1 shows a comparison between the atmospheric Argon (AA, red) and the underground Argon (blue) spectra, as measured at the KURF underground laboratory. The derived depletion factor is $\geq$ 150 [8].

- Application of a compact high efficiency external veto for neutrons [9]. DARKSIDE-50 is the first (and to date the only) experiment with the Dark Matter detector operated inside an active neutron veto. It is made by a 4 m diameter sphere filled with 30 t of organic liquid scintillator and equipped with low-radioactivity 110 8″ PMTs. The solution is made by 50% Pseudocumene (PC) and TriMetylButadiene (TMB), the latter being a molecule loaded with Boron, with a very high neutron capture cross section. PPO in 5 g/l concentration is added to reduce the light quenching. This system gives DARKSIDE-50 unique capability of tagging and rejecting with high efficiency events caused by radiogenic ($\geq$ 99.5%) and cosmogenic ($\geq$ 95%) neutrons masquerading as WIMP scatters.

- Assembly of the DARKSIDE detectors in a ^{222}Rn-free clean room. The first ^{222}Rn suppressed clean-room in the world was built at the Princeton University in 1998 - 1999 for the construction of the BOREXINO nylon vessels ($C_{Rn} \leq 1\,\mathrm{Bq/m^3}$ in the air inside) [10, 11]. The DARKSIDE collaboration has built two practically radon-free clean rooms in Hall C of LNGS, so-called Hanoi Cleaning Room (CRH) and Cleaning Room 1 (CR1). These rooms receive all their make-up air from a dedicated radon abatement system and are almost completely lined with stainless steel panels to limit radon emanation from the walls. The clean room CRH is located on top of the water tank and gives direct access into the muon and neutron vetoes through their top flanges. CR1 contains the equipment used for the cleaning and preparation of the DARKSIDE LAr-TPC parts [12]. Both clean rooms are sized to allow for preparation, assembly and deployment of a multi-ton TPC detector. A dedicated ^{222}Rn system has been developed to monitor on-line the ^{222}Rn content in the air assayed directly from the abatement system or from the clean-rooms. The measured values were at the level of $1\,\mathrm{mBq/m^3}$ and $2–20\,\mathrm{mBq/m^3}$, respectively [13], what makes the DARKSIDE clean room bests world-wide. For comparison, measurements of hall C air give typically $20–50\,\mathrm{Bq/m^3}$. Handling of parts and assembly of the DARKSIDE TPCs (as it happened for the DARKSIDE-50 TPC) in a ^{222}Rn-free environment is a part of the DARKSIDE background reduction strategy (preventing deposition of radioactive ^{222}Rn-daughters on the detector's surfaces).

The core of the DARKSIDE-50 experiment is a double phase TPC, 36 cm diameter and 36 cm height, filled with ~ 46.7 kg of LAr. Two arrays of 19 carefully selected low-radioactivity 3″ photo-multipliers are pointing to the center of the volume from the top and from the bottom surfaces. On the top of the liquid volume, a 1 cm height gas region is created by heating the LAr. A uniform electric field (200 V/cm) is maintained along the vertical axis of the cylinder and a stronger electric field is present is the gas region (2800 V/cm) for the extraction of ionization electrons. All the internal surfaces of the TPC are reflective and coated with TPB (ThetraPhenylButadiene), a wavelength-shifter required in order to convert the 128 nm LAr scintillation light in visible one, to match the photocathode sensitivity. Figure 2 shows schematically the DARKSIDE-50 TPC.

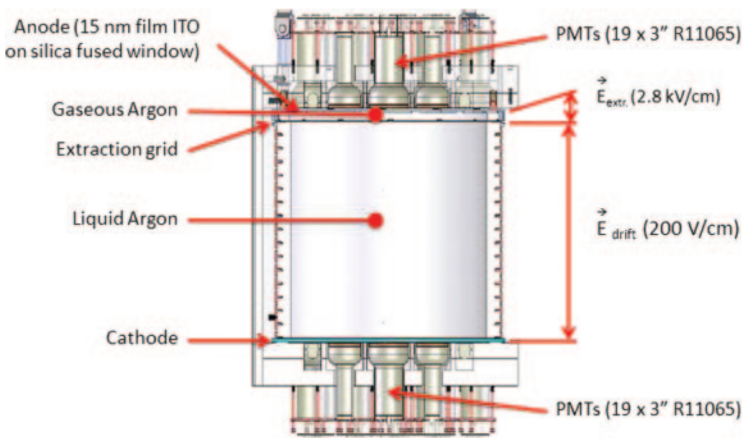

Fig. 2. – Schematic view of the DARKSIDE-50 Time Projection Chamber.

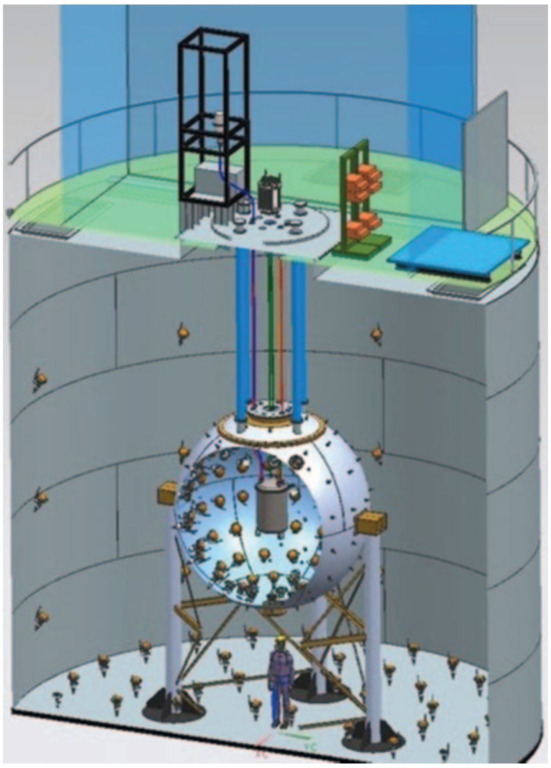

Fig. 3. – The nested detector system of DARKSIDE-50. The outermost is the water Cherenkov detector, the sphere is the neutron detector and the gray cylinder at the center of the sphere is the LAr TPC cryostat.

The cryostat (hosting the TPC) is placed inside the neutron detector and the latter one inside a tank containing ∼10 kt of high-purity water instrumented with 80 8″ PMTs (installed on the side and on the bottom). The water tank is acting as a Cherenkov detector for the surviving cosmic muons at the depth of the Laboratories. A sketch of the three nested detectors is shown in fig. 3.

3. – First results from the DARKSIDE-50 detector

The DARKSIDE-50 detector was filled with atmospheric argon and the data analyzsed here were accumulated between November 2013 and May 2014 [14]. The usable live-time, defined as all runs taken in Dark Matter search mode with a drift field of 200 V/cm and with all three detectors included, was (53.8 ± 0.2) d. Taking into account the applied cuts, reducing the live-time to (47.2 ± 0.2) d, the size of the fiducial volume of the detector ((36.9 ± 0.6) kg) and the overall acceptance ($0.82^{+0.01}_{-0.04}$), the total exposure was (1422 ± 67) kg × d ($\sim 1.5 \times 10^7$ ^{39}Ar events in the WIMP search energy region).

3˙1. *Detector calibrations*. – The main calibration of the detector has been realized with the insertion of ^{83m}Kr inside the Argon circulation loop. This isotope emits two low energy gammas for a total deposit of 41.5 keV (32.1 and 9.5 keV gammas appearing within 222 ns cannot be resolved) and has a mean life of 1.8 h. The position of the 41.5 keV peak over the ^{39}Ar β-spectrum allowed to measure the light yield of the detector to be (7.9 ± 0.4) p.e./keV without the electric field and about 7.0 p.e./keV at 200 V/cm. The stability of the detector response was also evaluated by selecting the events populating the ^{83m}Kr peak. While the maximum electron drift time for the 200 V/cm electric field is 375 μs (drift velocity of 0.93 mm/μs), the measured electron lifetime was larger than 5 ms proving high-purity of LAr. The internal non-uniformity both in terms of light and electrons collection have been evaluated as well. A calibration campaign with neutron (AmBe) and various gamma sources (^{57}Co, ^{133}Ba and ^{137}Cs) deployed in the neutron detector was also performed.

The WIMP acceptance region was determined by scaling the results from the SCENE experiment [15]. SCENE is dedicated to study the nuclear recoils in LAr. It is based on a small TPC exposed to a low energy pulsed narrow-band neutrons beam. The SCENE results were scaled to DARKSIDE TPC including all systematics effects related to differences in the detectors.

3·2. *Selection of events.* – A WIMP interacting inside the LAr active volume is expected to produce a nuclear recoil. As already mentioned, the main tool for rejecting electron recoils (reduction factor of about 10^8) that trigger the TPC is the PSD. Exploiting the S2/S1 ratio can increase the rejection power by an additional factor of 10^2–10^3. The most problematic source of WIMP-like events is represented by cosmogenic and radiogenic neutrons. Some of these events, those with multiple interaction inside the TPC, can be rejected since they produce a multiple ionization signal. The neutrons interacting only once in the TPC are likely to be captured inside the liquid scintillator neutron detector. A capture on ^{10}B (contained in TMB) results in the production of ^{7}Li and an α particle. Its energy of 1.47 MeV is quenched in the liquid scintillator to $\sim$50 keV. With a branching ratio of 94%, a 480 keV γ is also emitted. The measured light yield in the scintillator ($\sim$0.52 p.e./keV) is large enough to detect the α also when no γ is emitted. The number of cosmogenic neutrons that penetrate the veto undetected is negligible (basing on simulations). The major source of radiogenic neutrons are the PMTs and the total expected yield is about 100 n/y. From Geant4 based simulations, only 5×10^{-4} of them are expected to interact once in the TPC and to escape the veto without leaving any detectable signal (energy below 30 p.e.).

Fducialization is also applied to the active volume, in order to prevent contamination from α surface emissions (from raw materials qualification, they are expected to be $<10/(\mathrm{m}^2 \times \mathrm{d})$, removing events that are originated within 2 cm from the walls. After this cut, the ducial volume is reduced to 36.9 kg of LAr.

3·3. *WIMP region analysis.* – A scatter plot showing the data accumulated over the total live-time of 47.2 days is shown in fig. 4. The vertical axis represents the f90 PSD parameter (a fraction of the S1 signal appearing in the first 90 ns after the trigger) and the horizontal scales represent energy (in p.e. and keV$_r$) of S1 pulses. f90 is $\sim$0.3 for electronic recoils and $\sim$0.7 for nuclear recoils. The selected energy window for nuclear recoils extends from 60 to 460 p.e. corresponding to 40 to 200 keV$_r$ (or from from 8 to 40 keV$_{ee}$). The Dark Matter search box shown in the plot is obtained by intersecting the 90% nuclear recoil acceptance line from the SCENE experiment with the curve corresponding to a leakage of ^{39}Ar events of 0.01 events/(5-p.e.$\times$bin). The leakage curves are obtained by fitting the f90 distributions for any fixed energy according to the Hinkley model [16]. There are no events in the upper part of the plot, while a large number of electronic recoils (mainly due to the ^{39}Ar) populate the lower region.

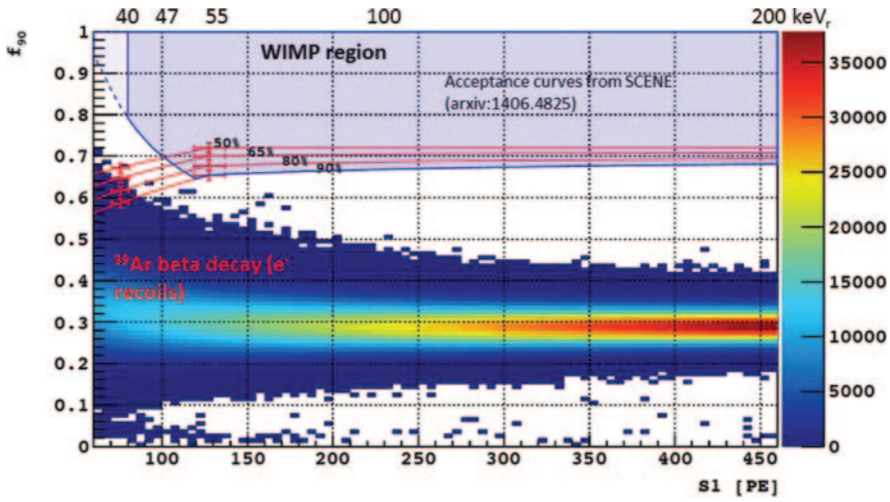

Fig. 4. – Distribution of the S1 events in the scatter plot of the f90 parameter *vs.* energy. Percentages label the f90 acceptance contours (DM box) for nuclear recoils drawn connecting points was determined from the SCENE measurements.

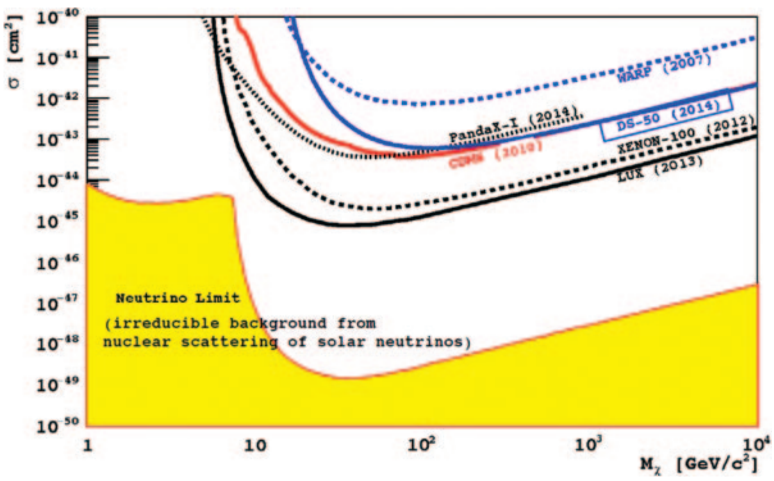

Fig. 5. – Spin-independent WIMP-nucleon cross section 90% C.L. exclusion plot for the DARKSIDE-50 atmospheric Argon campaign (solid blue curve) compared with results from other experiments. Also shown is an approximate band (yellow) where neutrino coherent scattering begins to limit the sensitivity of direct detection experiments to WIMPs.

This result has been obtained with atmospheric Argon runs and the collected statistics corresponds to roughly 20 years of DS-50 run with UAr. A first limit on the WIMP-nucleon cross section can be derived from these data, even if a physics result was not the main goal of this campaign. The limit, compared in fig. 5 with the current best results from other experiments, corresponds to $6.1 \times 10^{-44}\,\text{cm}^2$ (90% C.L.) for $100\,\text{GeV/c}^2$ WIMP mass and it is currently the most stringent one obtained with a LAr target.

4. – DARKSIDE prospects

The DARKSIDE-50 detector is successfully running with atmospheric argon and taking data since November 2013. The campaign is almost concluded and the data available so far provided a first physics result. Taking into account the PSD performance the reported exposure of $(1422 \pm 67)\,\mathrm{kg} \times \mathrm{d}$ with AAr, corresponds to about $215000\,\mathrm{kg} \times \mathrm{d}$ of running with UAr (a two-decade of ^{39}Ar background-free run with UAr). About 156 kg of UAr has also been delivered to LNGS. Replacement of AAr with UAr is expected for spring 2015. A three-year run with UAr is planned, which should confirm background-free performance of the detector.

The design of the next phase detector (multi-ton scale) is currently under discussion. The expected sensitivity for the WIMP-nucleon cross section will be of the order of $10^{-47}\,\mathrm{cm}^2$ at $1\,\mathrm{TeV/c}^2$ in a few years exposure.

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REFERENCES

[1] Gaitskell R. J., *Annu. Rev. Nucl. Part. Sci.*, **54** (2004) 315.
[2] Bertone G. and Merritt D., *Mod. Phys. Lett. A*, **20** (2005) 1021.
[3] Arina C. *et al.*, arXiv:1304.5119 (2013).
[4] Smith M. C. *et al.*, *Mon. Not. R. Astron. Soc.*, **379** (2007) 755.
[5] Cannoni M., arXiv:1108.4337 (2011).
[6] De Austri R. R. *et al.*, *JHEP*, **05** (2006) 002.
[7] DARKSIDE Collaboration (Akimov D. *et al.*), *Astropart. Phys.*, **49** (2013) 44.
[8] Xu J. *et al.*, arXiv:1204.6011 (2012).
[9] Calaprice F. *et al.*, *Nucl. Instrum. Methods A*, **644** (2012) 18.
[10] Pocar A., *Low Background Techniques and Experimental Challenges for BOREXINO and its Nylon Vessels*, PhD Dissertation, Princeton University (2003).
[11] Benziger J. *et al.*, *Nucl. Instrum. Methods A*, **582** (2007) 509.
[12] Bossa M., *JINST*, **9** (2014) C0103.
[13] Zuzel G., talk given at the *DARKSIDE General Meeting, Sardinia, Italy,* ^{222}*Rn detectors (June, 2014)*.
[14] DARKSIDE Collaboration (Agnes P. *et al.*)), *Phys. Lett. B*, **743** (2015) 456.
[15] SCENE Collaboration (Alexander T. *et al.*), *Phys. Rev. D*, **88** (2013) 092006.
[16] Lippincott W. H. *et al.*, *Phys. Rev. D*, **78** (2008) 035801.