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The DarkSide experiment

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Summary. — DarkSide is a dark matter direct search experiment at *Laboratori Nazionali del Gran Sasso* (LNGS). DarkSide is based on the detection of rare nuclear recoils possibly induced by hypothetical dark matter particles, which are supposed to be neutral, massive ($m > 10\,\mathrm{GeV}$) and weakly interactive (WIMP). The dark matter detector is a two-phase time projection chamber (TPC) filled with ultra-pure liquid argon. The TPC is placed inside a muon and a neutron active vetoes to suppress the background. Using argon as active target has many advantages, the key features are the strong discriminant power between nuclear and electron recoils, the spatial reconstruction and easy scalability to multi-tons size. At the moment DarkSide-50 is filled with ultra-pure argon, extracted from underground sources, and from April 2015 it is taking data in its final configuration. When combined with the preceding search with an atmospheric argon target, it is possible to set a 90% CL upper limit on the WIMP-nucleon spin-independent cross section of $2.0\times10^{-44}\,\mathrm{cm}^2$ for a WIMP mass of $100\,\mathrm{GeV}/c^2$. The next phase of the experiment, *DarkSide-20k*, will be the construction of a new detector with an active mass of ~ 20 tons.

1. – The existence of Dark Matter

The existence of dark matter, postulated since 1930 because of its gravitational effects on the dynamics of galaxies and clusters of galaxies, is today widely accepted and confirmed also on the cosmological scale. It is assumed that the dark matter is part of the missing mass of the Universe, but its nature is still completely unknown. At the moment the most precise measurement of the CMB, combined with the results from large-scale structure observations, indicates that dark matter and dark energy contribute respectively to 26.8% and 68.3% of the mass/energy density of the Universe leaving only 4.9% to the ordinary matter [1]. Among a wide range of possible theories and dark matter candidates one of the most shared hypothesis is that the galactic halo could be permeated of massive particles called WIMP. The term WIMP indicates candidates from different theoretical models, but with common characteristics: WIMPs are supposed to be stable and electrically neutral, they interact through gravitational force and they may have other unknown interactions of weak intensity. According to these properties WIMPs could interact with target nuclei of experiments releasing energies of order few tens of keV. Very low interaction rates are expected for such particles, based on the model for their production and existing limits [2]. To detect these WIMPs, target masses of $0.1-10$ tons may be required, and ultra-low background must be achieved by a combination of

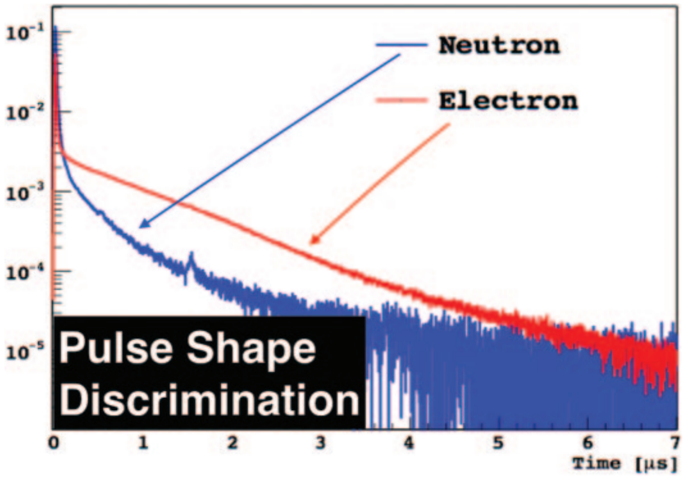

Fig. 1. – Time profile of the scintillation light: the electron recoil (red) has a bigger fraction of long-lived triplet states, so it is slower with respect to the nuclear recoil (blue) which has more short-lived singlet states.

measures. These include cosmic ray suppression by locating the experiments deep underground, selection of materials for low radioactivity, and instrumentation that can reject residual radioactive backgrounds in favor of the sought-after nuclear recoil events.

2. – The argon choice

In DarkSide the active medium for detection is liquid argon which is very suitable as target material for DM experiments because it has high scintillation yield, is easily purified of radioactive impurities and is likely scalable to large masses with relative ease. Among the noble gases argon also has excellent ionization and scintillation properties: in fact, a particle can produce more than 10^4 photons per MeV of deposited energy. Scintillation is initiated both by excitation and recombination after ionization. The 128 nm scintillation photons are emitted from two nearly degenerate excimer states, a long-lived triplet state and a short-lived singlet state. The difference in ionization density between nuclear recoils (from WIMP or neutron scattering) and electron recoils (from β/γ radiation) produces a significant difference in the radiative decay ratio of these states and hence in the time profile of the scintillation light [3]. Nuclear recoils have more of the fast scintillation component than electron recoils, providing a very powerful "pulse shape discrimination" (PSD) between electron backgrounds and nuclear-recoil signals (fig. 1).

The pulse shape discrimination between electron recoil and nuclear recoil is based on the F90 parameter, defined as the fraction of the scintillation signal in the liquid phase (S1) that occurs in the first 90 ns of the pulse, which is typically ~ 0.3 for β/γ-events and ~ 0.7 for nuclear recoils. For β/γ-events, the low density of electron-ion pairs also results in less recombination and therefore more free electrons, compared to a nuclear recoil track of the same S1 [4].

However, the high performances of the background rejection are strongly limited if atmospheric argon is used to fill the detector. That is because atmospheric argon, produced industrially by distillation of liquid air, contains ^{39}Ar, an isotope made by

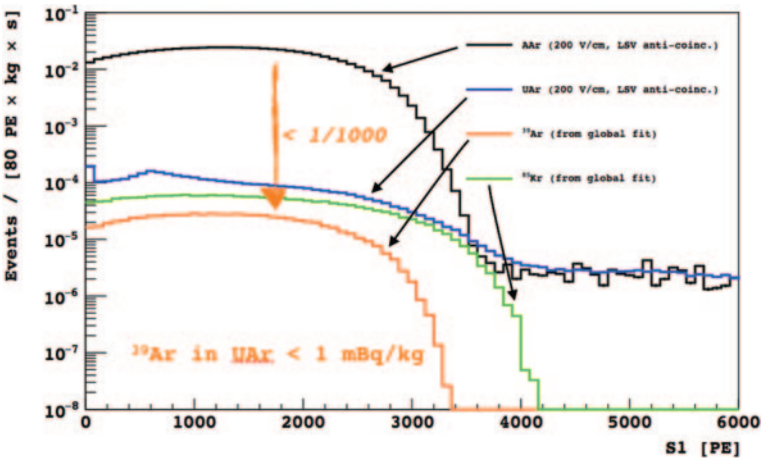

Fig. 2. – Comparison between the atmospheric argon and the underground argon spectrum. The black spectrum is dominated by ^{39}Ar. The lower line is the ^{39}Ar extracted using a Monte Carlo simulation.

cosmic ray activity. ^{39}Ar has, in air, a relative abundance $^{39}\text{Ar}/\text{Ar} = 8 \cdot 10^{-16}$ and it decays β^- ($Q = 565\,\text{keV}$ and $\tau = 388$ years) with an activity of $\sim 1\,\text{Bq/kg}$. The presence of ^{39}Ar does not only increase the background rate, but acting as an impurity, it limits the sensitivity of the experiment because favors electron recombination. To solve this problem the DarkSide collaboration made a multi-year effort to extract argon from underground sources: underground argon contains a factor of $\sim 10^3$ less ^{39}Ar with respect to atmospheric argon. The detector has been filled with underground argon between March and April 2015 and measures (fig. 2) confirm that the ^{39}Ar activity of UAr is a factor $(1.4 \pm 0.2) \times 10^3$ lower than the AAr one, corresponding to (0.73 ± 0.11). mBq/kg.

3. – DarkSide

The DarkSide project is designed for direct detection of dark matter particles, using a dual phase liquid argon time projection chamber. The whole experiment is based on three nested detectors: the double-phase TPC is surrounded by two veto detectors that are used to reject events in the TPC caused by cosmogenic (muon-induced) neutrons or by neutrons and γ-rays from radioactive contamination in the detector components.

The DarkSide main detector will be DarkSide-20k that is going to be a large scale time projection chamber with a fiducial mass of ~ 20 tons. The scintillation signal in argon will be detected by SiPM. The quantity of purified argon necessary to fill the detector will be extracted by a distillation column installed in the Seruci mine, in Sardinia.

At the moment, after the promising results of its predecessor DarkSide-10, the detector in use is DarkSide-50 [5].

3·1. *TPC.* – The cylindrical TPC, with an active UAr mass of (46.4 ± 0.7) kg is observed by thirty-eight 3″ PMTs positioned at the top and bottom of the TPC itself. An interaction in the LAr target generates primary scintillation light and ionization electrons. The electrons escaping recombination drift in the TPC electric field to the

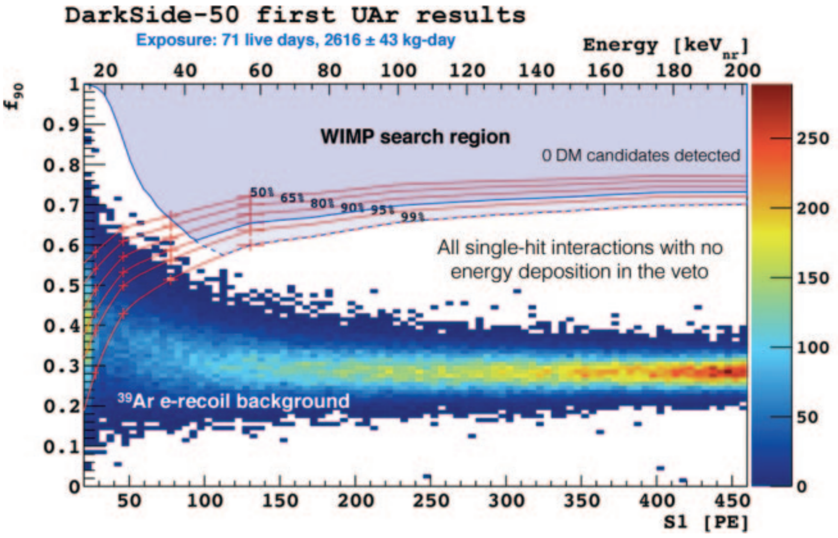

Fig. 3. – Plot of the f90 discrimination parameter: in the region of interest for the dark matter search DarkSide-50 is background free. See [6].

surface of the liquid argon, where a stronger electric field extracts them into the gaseous argon. In this field the electrons gain sufficient energy to induce further light emission via proportional scintillation.

So there are two kind of signal that have to be detected inside the TPC:

- The primary scintillation (S1) in the liquid phase, due to excitation and recombined ionization.

- The secondary scintillation (S2) in the gas phase, due to drifted ionization electrons.

The S1 and S2 pulses together allow the interaction point to be localized in 3D. The transverse (xy) position is determined from the distribution of the S2 pulses over the top PMT array, while the vertical (z) position is inferred from the drift time separating the S1 and S2 pulses.

3·2. *Neutron veto.* – The LSV is a 4.0 m diameter stainless steel sphere filled with 30 metric tonnes of boron-loaded liquid scintillator. The sphere is lined with Lumirror, a reflecting foil used to enhance the light collection efficiency. An array of 110 8″ PMTs is mounted on the inside surface of the sphere to detect scintillation photons. The purpose of the neutron veto is to tag neutrons which could produce in the TPC a nuclear recoil which can mimic the WIMP-nucleus interaction. The presence of TMB in the liquid scintillator mixture favours neutron capture on ^{10}B producing α particles of energy 1.47 MeV, corresponding to a signal of about 30 PE which can be easily detected.

3·3. *Muon veto.* – The LSV is located in the middle of a water Cherenkov muon veto (WCV), used for rejecting the coincidences in the TPC induced by the residual flux of cosmogenic muons and also used as passive shielding for external neutrons and gammas.

4. – First results

A first run of DarkSide-50 with a (1422 ± 67) kg-day exposure of atmospheric argon produced a null result for the dark matter search and zero backgrounds from ^{39}Ar decays. A total of 16 million background events in the 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 primary-scintillation pulse shape discrimination (PSD). The two remaining events in the WIMP search region had a signal in coincidence with the veto and were therefore discarded. The first WIMP search in DarkSide-50 using UAr has been also reported in [1], where it is shown that underground argon is depleted in ^{39}Ar by a factor $(1.4 \pm 0.2) \times 10^3$ relative to atmospheric argon. 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.

Dark matter limits from the present exposure are determined from our WIMP search region using the standard isothermal galactic WIMP halo parameters. Given the background-free result (fig. 3), we derive a 90% CL exclusion curve corresponding to the observation of 2.3 events for spin-independent interactions. When combined with the null result of our previous AAr exposure, we obtain a 90% CL upper limit on the WIMP-nucleon spin-independent cross section of $2.0 \times 10^{-44}\,\mathrm{cm}^2$ for a WIMP mass of $100\,\mathrm{GeV}/c^2$ [6].

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