Low-Mass Dark Matter Search with the DarkSide-50 Experiment
P. Agnes et al. (DarkSide Collaboration)
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Low-mass Dark Matter Search with the DarkSide-50 Experiment

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We present the results of a search for dark matter WIMPs in the mass range below 20 GeV/c^2 using a target of low-radioactivity argon with a 6786 kg d exposure. The data were obtained using the DarkSide-50 apparatus at Laboratori Nazionali del Gran Sasso (LNGS). The analysis is based on the ionization signal, for which the DarkSide-50 time projection chamber is fully efficient. The observed rate in the detector at 0.1 keV_{ee} is about 1.5 event/keV_{ee}/kg d and is almost entirely accounted for by known background sources. We obtain a 90% C.L. exclusion extending the exclusion region for dark matter below previous limits in the range 1.8–6 GeV/c^2.

The concept of dark matter was developed [1–3] more than 80 years ago to explain anomalous motions of galaxies gravitationally bound in clusters. Observational evidence has continued to accumulate since then, including rotation curves of galaxies and their clusters [4] and discrepancies in the distributions of galaxy cluster mass estimated from luminosity vs. gravitational lensing [5–7]. That this matter is not only dark but also cold and nonbaryonic is strongly implied by simulations of observed large-scale structure in the universe [8], fluctuations in the cosmic microwave background radiation [9], big bang nucleosynthesis [10, 11], and analysis of the Lyman-α forest [12].

One of the most favored dark matter candidates is the Weakly Interacting Massive Particle (WIMP) [13, 14], which explains the current abundance of dark matter as a thermal relic of the big bang. Most models predict dark matter WIMP masses near the electroweak scale of 100’s of GeV/c^2. However, dark matter particle masses ≤ 10 GeV/c^2 can also be compatible with experimental constraints if a significant asymmetry between dark matter and their anti-particles existed in the early universe [15]. There are claims of detection or possible detection in this mass range [16–18].

Previous Dark Matter (DM) searches with DarkSide-50 [19, 20] used pulse shape discrimination (PSD) on the primary scintillation signals (S1) to suppress electron recoil backgrounds, achieving a background-free condition for DM-induced nuclear recoils. Those analyses were sensitive to recoiling argon atoms in the energy range from 13 keV_{nr} to 201 keV_{nr}, confining the sensitivity to masses above...
a few tens of GeV/c^2. Here we present a search for DM with a much lower recoil analysis threshold, down to 0.6 keVnr, sensitive to DM masses down to 1.8 GeV/c^2. WIMPs in this mass range produce nuclear recoils well below 10 keVnr, where the efficiency for detecting the S1 signal is low and PSD is therefore not available. The required low recoil-energy analysis threshold is achieved by exploiting the gain inherent in the ionization (S2) signal of the dual-phase liquid argon time projection chamber (LAr TPC). Similar analyses have been presented from dual-phase liquid xenon time projection chambers [21].

The DarkSide-50 LAr TPC and its veto system are described in Ref. [19]. The TPC has 38 3″ PMTs (19 above the transparent anode of the TPC and 19 below the transparent cathode) viewing a (46.4 ± 0.7) kg active target of low-radioactivity underground argon (UAr) [22–25]. Light signals are detected from both primary UAr scintillation (S1) and gas-proportional scintillation (S2) from ionization electrons extracted into a vapor layer above the liquid. The data reported here were acquired between April 30, 2015, and April 25, 2017, using a TPC drift field of 200 V/cm, an extraction field of 2.8 kV/cm, and an electroluminescence (EL) field of 4.2 kV/cm. At this extraction field, the efficiency for extracting ionization electrons into the gas layer is estimated at >99.9 % [26]. The exposure for the present search including cuts (see below) is 6786.0 kg d.

The LAr TPC lies at the center of a sensitive veto system [27–29]. The TPC is immersed in a 4.0 m diameter liquid scintillator veto (LSV) filled with 30 t of boron-loaded liquid scintillator and instrumented with 110 PMTs. Surrounding the LSV is a 1 kt Water Cerenkov Veto (WCV) instrumented with 80 PMTs. The veto system acts as a highly effective passive shield against local sources of radioactivity. We note that the signals from these detectors are not used in the event analysis because, due to the electron drift time in the TPC, the S2 triggers are not in prompt coincidence with the veto.

The detector has been calibrated in situ using γ and (α,n) neutron sources positioned inside the LSV next to the TPC [29]. Data taken with ^57Co, ^133Ba, and ^137Cs γ-ray sources are used to validate the Monte Carlo (MC) simulations, and ^241AmBe and ^241Am^13C neutron source data are used to verify the nuclear recoil and veto response. Calibrations were also carried out with ^83Kr diffused throughout the TPC [30].

We have developed G4DS [31], a Geant4-based [32, 33] MC code, which describes the performance of the three DarkSide detectors, accounting for material properties, optics, and readout noise. G4DS also includes a model for LAr scintillation and recombination. The MC is tuned to agree with the high statistics ^35Ar data from the atmospheric argon (AAr) exposure of DarkSide-50 [19].

Some simple quality cuts were applied to the data before analysis. Short runs, data where less than the full complement of TPC PMTs was active, and runs with an abnormal trigger rate or with excessive noise on the PMT signal baselines were discarded.

A hardware event trigger in DarkSide-50 occurs when 2 or more PMT signals exceed a threshold of 0.6 PE within a 100 ns window. Subsequent triggers are inhibited for 0.8 ns, and waveform data are recorded from all 38 PMTs for 440 µs starting ~10 µs before the trigger [34]. Software pulse finding algorithms are then applied to the digitized data including the pre-trigger data. The software classifies pulses into two categories (S1 or S2) based on the fraction of light detected within the first 90 ns (f90). S1 pulses have f90 values greater than 0.15, as opposed to the much slower-rising S2 pulses. Unlike previous analyses [19, 20], which required both an S1 and an S2 pulse, this analysis achieves a lower energy threshold by accepting not only events with a single S1 and S2 pulse but events with only an S2 pulse.

The efficiency of the software pulse finding algorithm is essentially 100% for S2 signals larger than 30 PE [19, 35]. The pulse finder uses an integration window of 30 µs, which is long enough to collect the entire S2 signal including the slow component with its decay time in gas of ~3.4 µs [36]. The pulse integration starts 2 µs before the start time of pulses defined by the pulse finding algorithm in order to fully collect the light of slow rise time S2 pulses.

Fiducialization in the present analysis is complicated by the low recoil energy region of interest. S1 pulses are not usually large enough to be detectable, so no drift time (time between S1 and S2 pulses) is available for z-fiducialization. The usual algorithm for reconstructing the x-y position from the S2 light distribution also fails at low recoil energy due to low photoelectron statistics. Instead, we assign the x-y position of each event to be at the center of the PMT receiving the largest number of S2 photoelectrons. We then set a fiducial region in the x-y plane by only accepting events where the largest S2 signal is recorded in one of the seven central top-array PMTs.

We reject a small number of events that have a large S1 pulse, even when accompanied by an abnormally low S2 pulse that would, on its own, fall in the region of interest. These events occur near
with the same cuts applied to 39. This matches the acceptance of (0 ± 43) of the restricted fiducial region.

The S2 photoelectron yield per extracted ionization electron, \( \eta \), is determined by studying single electron events obtained during a short period of time in which the inline argon purification getter was turned off for maintenance purposes (Fig. 2). These runs have a significantly enhanced single-electron event rate. The observation of strong time and space correlations between single-electron events and preceding large ionization events leads us to believe that these events are from electrons captured by and subsequently released from trace impurities in the argon [37–39]. We obtain \( \eta = (23 \pm 1) \) PE/e\(^-\) for events localized beneath the central PMT, where the error combines variation throughout the entire campaign as well as systematics.

The rates at which ionization electrons are trapped and subsequently released are found to be \( (3.5 \pm 0.3) \times 10^{-5} \) e\(^-\)/e\(^-\) when the getter is off and \( (0.5 \pm 0.1) \times 10^{-5} \) e\(^-\)/e\(^-\) when the getter is active normalized to the total yield of ionization electrons. The electron lifetime was \( \sim 10 \) ms over the entire data taking period, equivalent to \( \sim 30 \) ppt O\(_2\) contamination. We ignore data taken where the getter is off and to reduce spurious events from these delayed electrons in standard running, we reject events which occur less than 2.5 ms after a preceding trigger. The resulting loss of exposure is about 1%.

Because of an observed radial variation in the electroluminescence yield, a correction is applied to the S2 photoelectron yield for events that originate under the six PMTs surrounding the central one. This correction to the number of extracted electrons, \( N_{e^-} \), was determined using calibrations performed with a mono-energetic (41.5 keV) \(^{83m}\)Kr source to be \( N_{e^-} = S2 / (0.76 \cdot \eta) \).

The \( N_{e^-} \) distributions expected for different numbers of extracted electrons are modeled with G4DS and are well described by Gaussians. The simulated responses for one and two electrons are in good agreement with the getter-off data. Fig. 2 shows the comparison of the G4DS one- and two-electron distributions with the event distribution in data.

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**FIG. 1.** Acceptance of the basic cuts described in the text as a function of the number of PE in the pulses.

**FIG. 2.** Filled symbols show DarkSide-50 experimental \( N_{e^-} \) spectra obtained during the last 100 days of data taking and (open symbols) during the short period where the getter was off for maintenance. Both the single- and double-electron peaks are seen to be strongly enhanced in the absence of argon purification. Smooth black curve shows a weighted sum of the G4DS one-, two-, and three-electron responses.
The separate contributions from events with a single S2 and those with S1+S2 from the 500-day sample are also shown in Fig. 3. The tail of single S2 events extending above 50 e$, amounting to about 4% of the total rate, is due to unresolved S1+S2 events. These events are mis-categorized but do not affect the total spectral shape. The spike at very low N$_{e^-}$ is attributed to electrons trapped by impurities and then released, as discussed above.

In situ calibration data from $^{241}$Am$^{13}$C and $^{241}$AmBe neutron sources [48] and neutron-beam scattering data from the SCENE [49, 50] and ARIS [51] experiments are used to determine the ionization yield from nuclear recoils, Q$_{y}$.

The use of $^{241}$Am sources for calibration is complicated by the flux of $\gamma$-rays produced in the sources. In the case of the $^{241}$Am$^{12}$C source, the $\gamma$-ray background is reduced by restricting the data to the 4 PMTs farthest from the source and the remaining $\gamma$ contamination is estimated using G4DS, an estimate which is validated by comparison with the data at an energy above any nuclear recoil. In the case of the $^{241}$AmBe calibration, events in the TPC are accepted only if they were in coincidence with detection of the 4.4 MeV $\gamma$ in the veto, a requirement which effectively singles out a pure neutron recoil sample. The inevitable loss of events (98%) that arises because the signal in the veto is coincident with the S1 signal while the low-energy S2 trigger is delayed by the drift-time in the TPC is manageable given the size of our data-set.

The final $^{241}$Am$^{13}$C and $^{241}$AmBe N$_{e^-}$ spectra are fit simultaneously to recoil energy distributions by G4DS using the model of Bezrukov et al. [52] to convert nuclear recoil energy to ionization. The model has two free parameters which relate to a combination of the energy quenching and the ionization to excitation ratio and the recombination rate of ionization pairs. For the $^{241}$Am$^{13}$C data these two parameters are sufficient and the fit goes to the analysis threshold of 4 electrons. The fit for the $^{241}$AmBe data, however, also includes a term for the acceptance of the coincidence requirement and a strong correlation is noted between the uncertainties on the acceptance-loss model and the ionization response. To avoid this correlation, the fit to the $^{241}$AmBe data has a threshold of 50 e$, above which the fraction of S2 triggered data is negligible. The resulting fits are shown in Fig. 4 and Fig. 5 for the $^{241}$AmBe and the $^{241}$Am$^{13}$C source respectively. The simulated distributions fit the data well and provide strong constraints for the ionization yield.
the curve represents the -1 σ uncertainty from the fit. The upper boundary of the shaded region is drawn to represent the ionization predicted using the same model but fitting to the neutron-beam scattering measurements. The difference between the curve and the upper boundary is taken as our systematic uncertainty and is included in the profile likelihood analysis described later. The ionization yield measured with 241AmBe and 241Am13C neutron sources in DarkSide-50 is systematically lower than the ionization yield from SCENE and ARIS. The choice of Q0 extracted from 241AmBe and 241Am13C in this analysis leads to a conservative estimate of the exclusion limits.

Fig. 7 shows the N_e− spectrum for the last 500 days (same as blue histogram in Fig. 3) together with the contributions from the individual radiation sources from the simulation, normalized using the detector construction materials radioassay data and radioactivity estimation obtained by fitting gamma lines at high energy, 39Ar, and 85Kr spectra. The N_e− distribution from the 500 day sample obtained with the present analysis is consistent within uncertainties with the G4DS MC fit to the 241AmBe and 241Am13C data (see text).

The observed DarkSide-50 rate as a function of keV_{ee} is flat at ~1.5 events/(keV_{ee} kg d) in the range from 0.1 keV_{ee} to 10 keV_{ee}. The large (10^2) increase below 0.1 keV_{ee} is believed to be from electrons trapped and subsequently released by impurities. This is based on the observation of a strong time correlation between a higher energy event and the following low N_e− events, suggesting electrons are released from impurities with a ~50 ms time constant. Also shown in Fig. 7 are the N_e− spectra expected for nuclear recoils induced by dark matter particles of masses 2.5, 5, and 10 GeV/c^2 with a cross section of 10^{-40} cm^2 and standard isothermal halo parameters (v_{escape} = 544 km/sec, v_0 = 220 km/sec, v_Earth = 232 km/sec, and \rho_{DM} = 0.3 GeV/(c^2 cm^3) [55]).

Uncertainties in the expected signal yield above the analysis threshold are dominated by the average ionization yield as extracted from the 241AmBe and 241Am13C data and its intrinsic fluctuations. We have no a priori knowledge of the width of the ionization distribution of nuclear recoils and are not aware of measurements in liquid argon in the energy range of interest. We therefore consider two extreme models: one allowing for fluctuations in energy quenching, ionization yield, and recombination processes obtained with binomial distributions and another where the fluctuations in energy quenching are set to zero, equivalent to imposing an analysis threshold of 0.59 keV_{nr}.

Extrapolations of the expected background to the signal region are mostly affected by theoretical un-
diverge because of the effective threshold due to the sensitive to the choice of quenching fluctuation model.

Dashed line) are shown in Fig. 8. For masses above 10^{-40} cm^2 convolved with the no energy quenching fluctuation model and detector resolution. The y-axis scales at right hand side are approximate event rates normalized at N_e^- = 10 e^-.

certainties on the low energy portion of the ^{85}Kr and ^{34}Ar β-spectra and by the uncertainty in the electron recoil energy scale and resolution.

Upper limits on the WIMP-nucleon scattering cross-section are extracted from the observed N_e^- spectrum with a binned profile likelihood method [56–58]. Two signal regions are defined, the first one using a threshold of 4 e^-, determined by the approximate end of the trapped electron background spectrum, and the second above a threshold of 7 e^-, where the background is described within uncertainties by the G4DS simulation. The first region has sensitivity to the entire range of DM masses explored in this work, but the data is contaminated by a component that is not included in the background model, resulting in weaker bounds on the DM-nucleon cross-section. The second signal region has limited sensitivity to DM masses below 3.5 GeV/c^2 but, due to the agreement between data and background model, more tightly constrains the cross-section at higher masses. For a given fluctuation model and DM mass, we calculate limits using both signal regions and quote the more stringent of the two.

The 90% C.L. exclusion curves for the binomial fluctuation model (red dotted line) and the model with zero fluctuation in the energy quenching (red dashed line) are shown in Fig. 8. For masses above 1.8 GeV/c^2, the 90% C.L. exclusion is nearly insensitive to the choice of quenching fluctuation model. Below 1.8 GeV/c^2, the two exclusion curves rapidly diverge because of the effective threshold due to the absence of the fluctuations in the energy quenching process. Without additional constraints on the quenching fluctuations, it is impossible to claim an exclusion in this mass range.

Our exclusion limit above 1.8 GeV/c^2 is compared with the 90% C.L. exclusion limits from Refs. [21, 59–73], the region of claimed discovery of Refs. [17, 74–76], and the neutrino floor for LAr experiments [77]. Improved ionization yield measurement and assessment of a realistic ionization fluctuation model, which are left for future work, may be used to determine the actual sensitivity of the present experiment within the range indicated by the two curves below the 1.8 GeV/c^2 DM mass.

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