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WIMP Search With the Final Year of CDMS II Data

L. HSU for the CDMS collaboration
Fermi National Accelerator Laboratory, Batavia, IL 60510, USA

The Cryogenic Dark Matter Search (CDMS) has pioneered the use of ionization and athermal phonon signals to discriminate between candidate (nuclear recoil) and background (electron recoil) events in Ge crystals cooled to ∼50 mK. The yield and timing information allows for the maximization of discovery potential by adjusting the expected background in the signal region to less than one event. A blind analysis on 612 kg-days of raw exposure from the CDMS II experiment was performed. Two events with an expected background of ∼0.9 events were observed. No statistically significant evidence for WIMP interactions is reported. Combining this data with previously analyzed CDMS II data sets an upper limit on the WIMP-nucleon spin-independent cross-section of 3.8×10^{-44} cm^2 for a WIMP of mass $70\,\mathrm{GeV/c^2}$.

1 Overview

A host of astrophysical observations have established a modern concordance model of the universe known as ΛCDM cosmology. This model prescribes that less than 4% of today's universe is made of baryonic matter. Of the remaining mass-energy budget, 23% can be attributed to cold dark matter and the other 73% to dark energy [1]. Although it is most of the matter in the universe, much of what we know about dark matter is inferred soley from its gravitational interactions. Weakly interacting massive particles (WIMPs) are a theoretically favored candidate to explain the identity of dark matter. Such particles are strongly motivated by the observation that particles with mass and annihilation cross-section at the weak interaction scale naturally yield the correct relic abundance of dark matter [2]. These particles are also independently postulated through proposed extensions to the Standard Model of particle physics [3,4].

WIMPs, distributed in a halo surrounding our galaxy, are expected to coherently-scatter off nuclei in terrestrial detectors [5,6,7] with a mean recoil energy of several tens of keV [8]. Experimental data limit the cross section for WIMP-nucleon interactions to be less than one WIMP interaction per year per kg of interacting material. Direct detection experiments like CDMS search for nuclear recoils from such dark matter interactions.

CDMS operates an array of 19 Ge (∼230 g) and 11 Si (∼100 g) particle detectors at cryogenic temperatures ($<$ 50 mK) in the Soudan Underground Laboratory. CDMS derives its sensitivity to WIMPs by maintaining ultra-low background levels. The depth of the experimental facility (713 meters below the surface) greatly reduces the probability of mistaking an isolated neutron scatter from cosmic ray spallation as a WIMP scatter. Nearly all remaining events from cosmic ray activity are identified using a layer of plastic scintillator surrounding the detector volume. Inner layers of lead and polyethylene further shield the detectors against environmental radioactivity.

Particle interactions in the detectors deposit energy in the form of phonons and ionization. Nuclear recoils generate less ionization than electron recoils of the same deposited energy, allowing event-by-event rejection of electron-recoils, which are the primary source of intrinsic background. Phonon sensors on the top of each detector are connected to four readout channels to allow measurement of the recoil energy and position of an event. The electric field for the ionization measurement is formed by applying a voltage bias to the bottom detector surface, which is segmented into two concentric electrodes. The phonon sensors serve as the ground reference for the ionization measurement. Events having an ionization signal in the outer ionization channel of the detector are excluded, defining an ionization fiducial volume. The detectors are grouped into five towers, each tower containing six detectors. Detectors are identified by their tower number (T1-T5) and their position within that tower (Z1-Z6). Intervening material between detectors within a tower are minimized to increase the probability of events scattering between detectors [9].

The ratio of the ionization to recoil energy ("ionization yield") provides event-by-event rejection of electron-recoils to better than 1 in 10^4. All of the remaining misidentified electron recoils are "surface events" occurring within the first few microns of the detector surface. These events suffer from sufficiently reduced ionization collection to be misclassified as nuclear recoils. Due to interactions of phonons in the surface metal layers, surface events have faster-rising phonon pulses than events occurring within the bulk of the detectors. We use phonon pulse timing parameters to improve rejection of surface events. This results in an overall (yield plus timing) misidentification probability of better than 1 in 10^6 for electron recoils [9 10 11].

2 Analysis of CDMS II Data

Data taken during four periods of stable operation between July 2007 and September 2008 were analyzed. A subset of events were analyzed to monitor detector stability and identify periods of poor detector performance. After data quality selections, the total exposure to WIMPs considered for this work was 612 kg-days [9].

A blind analysis was performed, in which cuts were developed without looking at events that might appear in the signal region. Candidate WIMP-scatters were required to be within 2σ of the mean ionization yield of nuclear recoils and at least 3σ away from the mean ionization yield of electron recoils, have recoil energy between 10 and 100 keV, and have ionization energy at least 4.5σ above the noise. The signal region in the primary background discrimination parameters, yield and timing, were defined using gamma (^{133}Ba) and neutron (^{252}Cf) calibration data as shown in Figure 1. Candidate events were required to occur within the detector fiducial volume, satisfy data quality criteria and pass the surface-event rejection cut. Since WIMPs are expected to interact only once in the experimental apparatus, a candidate event was required to have energy deposition consistent with noise in the other 29 detectors. To reject cosmic-ray induced events, we required the absence of significant activity in the surrounding scintillator veto shield during a 200-μs window around the trigger. The efficiency of the analysis cuts for nuclear recoils was measured as a function of energy using both neutron-calibration and WIMP-search data. After all selection criteria are applied, the spectrum-averaged equivalent exposure for a WIMP of mass 60 GeV/c^2 is 194.1 kg-days.

3 Results

After all selection criteria, the primary remaining background is from surface events. We estimated the surface event contribution in this exposure to be 0.8 ± 0.1(stat)± 0.2(syst) events. There is an additional, small, but non-negligible background contribution from cosmogenic neutrons of $0.04^{+0.04}_{-0.03}$(stat) events and from radiogenic neutrons of 0.03 to 0.06 events. Details of the background estimates may be found in the supporting on-line material of the peer-reviewed report that this proceedings is based on [9].

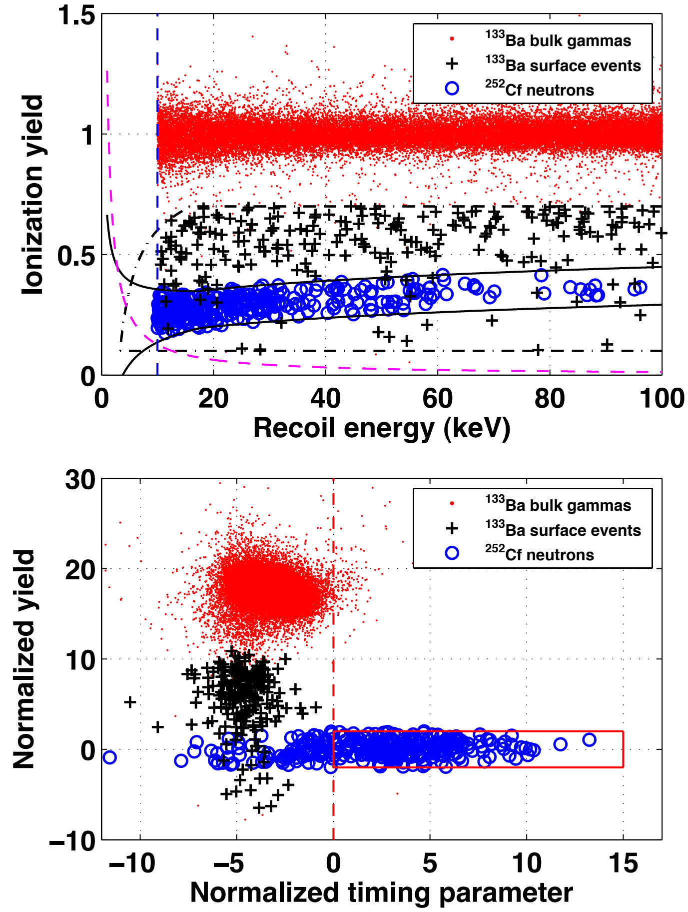

Figure 1: *In situ* calibration data were used to define the WIMP signal region in the primary discrimination parameters, yield and timing. Shown are bulk electron recoils (red points), surface electron events (black crosses) and nuclear recoils (blue circles) with recoil energy between 10 and 100 keV, for a typical detector. Top: Ionization yield versus recoil energy. The solid black lines define bands that are 2σ from the mean nuclear-recoil yield. The sloping magenta line indicates the ionization energy threshold while the vertical dashed line is the recoil energy analysis threshold. The region enclosed by the black dash–dotted lines defines the sample of events that were used to develop surface-event cuts. Bottom: Normalized ionization yield (number of standard deviations from mean of nuclear recoil band) versus normalized timing parameter (timing relative to acceptance region) is shown for the same data. Events to the right of the vertical red dashed line pass the surface-event rejection cut for this detector. The red box is the WIMP signal region.

After unblinding, we observed two events in the WIMP acceptance region at recoil energies of 12.3 keV and 15.5 keV. The candidate events, along with data from each of the analyzed detectors, are shown in Figure 2. Based on the expected background, the probability to have observed two or more surface events in this exposure is 20%; inclusion of the neutron background estimate increases this probability to 23%. These expectations indicate that the results of this analysis cannot be interpreted as significant evidence for WIMP interactions.

We calculated an upper limit on the WIMP-nucleon elastic scattering cross-section based on standard galactic halo assumptions [8] and in the presence of two events at the observed energies. We used the Optimum Interval Method [16] with no background subtraction. The resulting limit, shown on the LHS of Figure 3, has a minimum cross section of 7.0×10^{-44} cm^2 for a WIMP of mass 70 GeV/c^2 . This limit is strengthened to 3.8×10^{-44} cm^2 when combined with previous CDMS II results. We have also analyzed this data under the hypothesis of WIMP inelastic scattering [17], which has been invoked to explain the DAMA/LIBRA data [18]. We computed 90% C. L. DAMA/LIBRA allowed regions following a χ^2 goodness-of-fit technique [19], without

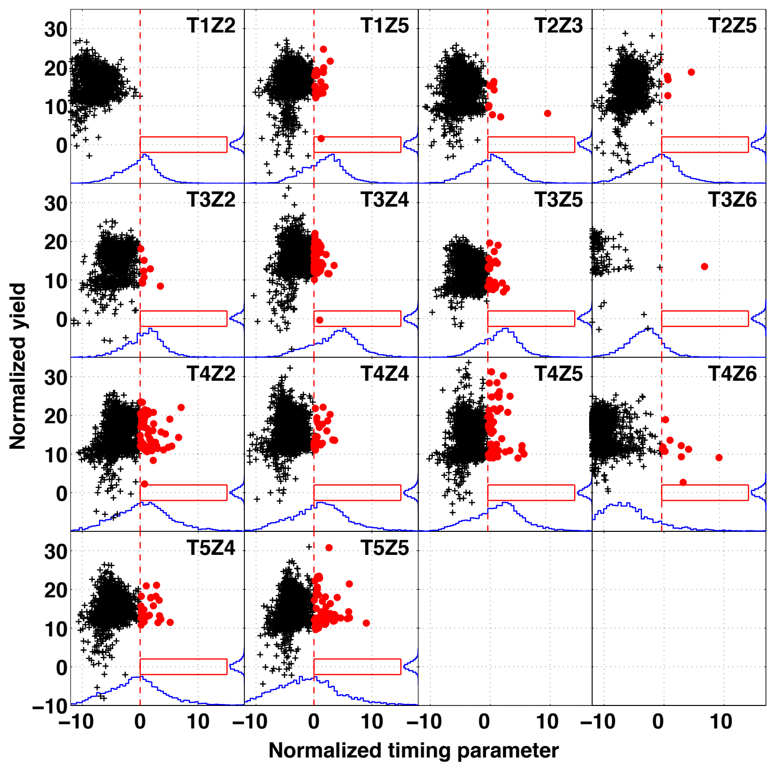

Figure 2: Normalized ionization yield (number of standard deviations from mean of nuclear recoil band) versus normalized timing parameter (timing relative to acceptance region) for all events that pass all cuts except for yield and timing. Each panel shows the data taken with the indicated detector. All detectors that were used in this reported WIMP search are shown. The events that pass the phonon timing cut are shown with round markers. The red boxes indicate the signal region for that detector. The candidate events occur on detectors T1Z5 and T3Z4. The blue histograms shows the expected distributions for nuclear recoils in each detector, as measured by the calibration data.

including channeling effects [20]. Limits from our data and that of XENON10 [21] were computed using the Optimum Interval Method [16]. Regions excluded by CDMS and XENON10 were defined by demanding the 90% C. L. upper limit to exclude the DAMA/LIBRA allowed cross section intervals for allowed WIMP masses and mass splittings. The results are shown on the RHS of Figure 3. The CDMS data disfavor all but a narrow region of the parameter space allowed by DAMA/LIBRA. This region resides at a WIMP mass of $\sim$100 GeV/c^2 and mass splittings of 80–140 keV.

The data presented in this paper constitute the final data runs of the CDMS II experiment. They double the analyzed exposure of CDMS II. The observation of two events leaves the combined limit, shown in Figure 3, nearly unchanged below 60 GeV/c^2. It allows for a modest strengthening in the limit above this mass and rules out new parameter space.

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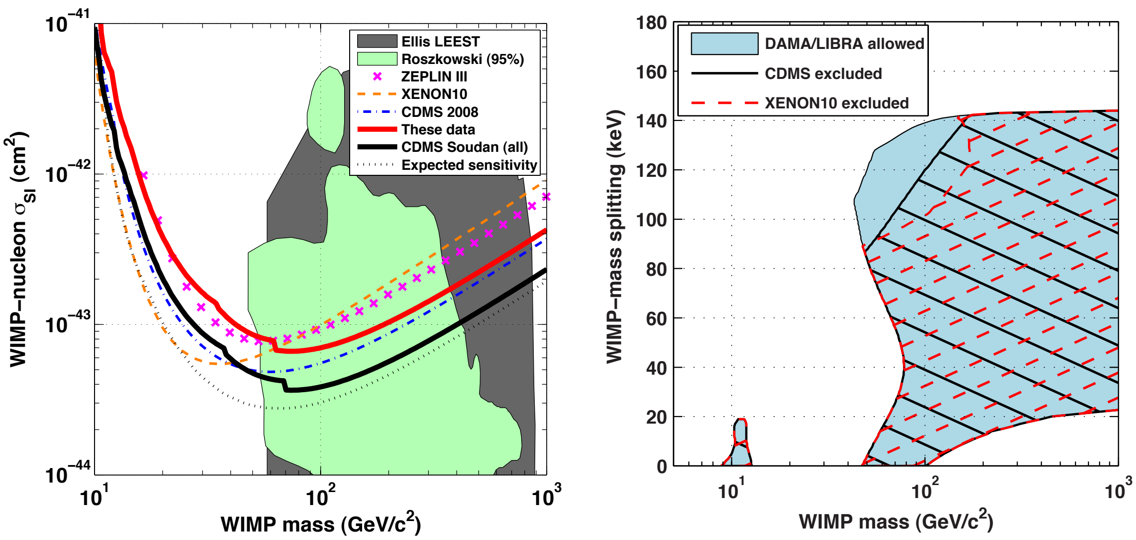

Figure 3: Experimental upper limits (90% confidence level) and theoretical allowed regions for the WIMP-nucleon spin-independent cross section as a function of WIMP mass [9]. The red (upper) solid line shows the limit obtained for the 612 kg-day raw exposure. The solid black line shows the combined limit for the full data set recorded at Soudan. The dotted line indicates the expected sensitivity for this exposure based on our estimated background combined with the observed sensitivity of past Soudan data. Prior results from CDMS [10], XENON10 [12], and ZEPLIN III [13] are shown for comparison. The shaded regions indicate allowed parameter space calculated from certain Minimal Supersymmetric Models [14] [15].

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