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Systematics of Low Threshold Modulation Searches in CDMS II

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Abstract

The Cryogenic Dark Matter Search experiment (CDMS II) used underground-based germanium and silicon detectors to search for the scattering of Weakly Interacting Massive Particles (WIMPs), which are among the leading candidates for the dark matter component of the universe. Using the ionization and athermal phonons measured in particle interactions, CDMS II was able to achieve excellent discrimination between the nuclear recoils expected for WIMP interactions and radioactively produced electron recoils. With the rise of interest in the low energy interactions of light mass WIMPs, the SuperCDMS collaboration has undertaken a search for an annually modulating signal at low thresholds in the CDMS II data. Previous results detailed the analysis of data from eight germanium detectors over the course of six runs, to thresholds of 5 keV_{nr} (nuclear recoil equivalent energy). We will discuss the impact of systematics at these low thresholds and their implications for thresholds down to 2.27 keV_{nr}.

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

Keywords: dark matter, WIMP, annual modulation, CDMS II

1. Introduction

Nearly 27% of the measured mass of the universe is believed to exist in the form of massive particles with nuclear interactions on the weak scale [1]. Among the favored candidates for this elusive mass component, termed "dark matter" for its lack of electromagnetic interaction, is the Weakly Interacting Massive Particle (WIMP). WIMPs naturally arise from many supersymmetric (SUSY) extensions to the standard model of particle physics [2] as cold particles with large relic density, forming large halos around galactic disks. The standard halo model (SHM) predicts an isotropic, spherical halo with mean particle velocity 220 km/s and density 0.3 GeV/cm^3. Solar motions through this dark matter halo result in an effective "WIMP wind" from the reference frame of an earth-bound observer, with a yearly modulation produced by the revolution of Earth about the sun [3]. Recent results in dark matter direct detection experiments form a puzzling view of the WIMP parameter space. The XENON100 [4] and LUX [5] collaborations report no signal and have set upper limits on the cross-section of interaction at $\sim 7.6\times10^{-46}$ cm^2 for a 33 GeV/c^2 WIMP, and the CDMSlite [6] and SuperCDMS low-threshold [7] analyses have set new limits on WIMP-mass interactions

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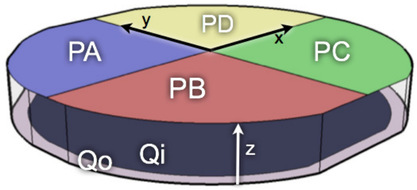

Fig. 1. Z-Ionization and phonon (ZIP) detector from CDMS II. Figure courtesy of S. Hertel [14].

below 10 GeV/c^2. Meanwhile, several experiments, including CoGeNT [8, 9, 10, 11], CRESST II [12], and CDMS II-Si [13], have reported excess events within the signal regions of their detectors (CDMS II not at discovery significance). The increase in interest surrounding low-energy, low-threshold interactions has led to an increase in the concentration on searches for low-mass WIMP interactions. The SuperCDMS collaboration has undertaken an analysis of its low threshold data from CDMS II for annual modulation in an attempt to provide further insight into the reconciliation of direct detection results in this low-mass regime.

2. The Cryogenic Dark Matter Search Experiment (CDMS II)

The CDMS experiment is located in the Soudan Underground Lab in Soudan, MN, USA. CDMS II, which ran from October 2006 until November 2008, was the second generation of the CDMS concept, with a complement of 19 germanium and 11 silicon detectors. CDMS II used "ionization yield", the ratio between the signals from ionization and from athermal phonons, to distinguish between electron and nuclear recoils in the search for WIMPs. Each detector was patterned with four phonon channels and two ionization channels (Fig. 1), which allowed readout of both phonons and charge for nuclear recoil discrimination, and provided depth and radial position information for event interactions throughout the detector. The outer ionization channel serves as a guard ring or outer veto, defining the fiducial region of the detector and improving the rejection of partially collected sidewall events, a significant contribution to the backgrounds in CDMS II.

For the low mass range, eight low-threshold germanium detectors were chosen for analysis (Fig. 2). The full complement of 30 detectors was used to veto multiple-scatter events. Results (Fig. 3) for a low-threshold analysis to 2.27 keV_{nr} (nuclear recoil equivalent energy) were published in 2010, establishing a spin-independent upper limit of $\sim 4 \times 10^{-41}$ for a WIMP mass of 8 GeV/c^2 [15]. This analysis reported no excess beyond the expected backgrounds.

3. The CDMS II search for annual modulation

Using the low-threshold data set defined during the CDMS II low-threshold germanium analysis, the CDMS collaboration searched for an annually modulating signal in CDMS II. While the traditionally expected hallmark of a WIMP signal is the presence of both an excess and modulation in the nuclear recoil event rate, detection of either signature may provide an important clue for the elimination of previously unexpected backgrounds at low thresholds, and provide some resolution of the tension between conflicting direct detection results. Results of the search for annual modulation in CDMS II above 5 keV_{nr} were reported in [16].

Above 5 keV_{nr}, the efficiency of the trigger thresholds for all eight of the low-threshold germanium detectors are essentially unity. Using this as the criterion for the low-energy threshold, a Feldman-Cousins analysis was conducted on veto-anticoincident, single-detector interactions up to 11.9 keV_{nr} in the WIMP-search data, and the magnitude of any modulation was constrained to less than 0.06 event$[keV_{nr}\,kg\,day]^{-1}$

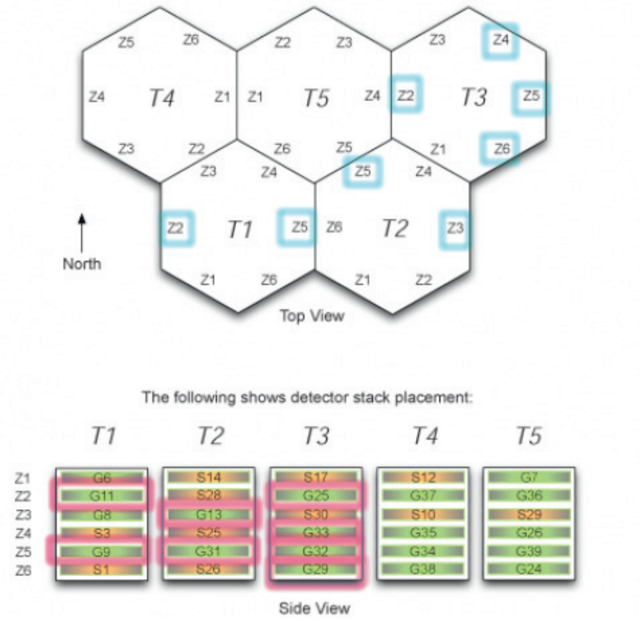

Fig. 2. CDMS II tower arrangement and detector selection for the low-threshold germanium analysis. Modification of figure by K. Sundqvist.

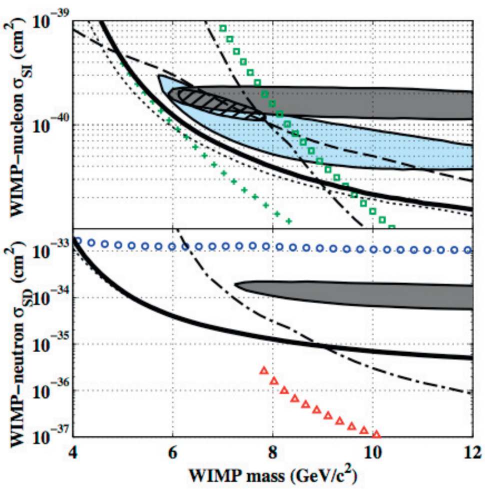

Fig. 3. 90% upper confidence limit (black) for spin-independent (SI, top) and spin-dependent (SD, bottom) WIMP-nucleus interactions in the CDMS II low-threshold germanium analysis. Figure from [15]. Additional SI limits shown include: limits from low threshold analysis of CDMS shallow-site data (dashed); CDMS II Ge results with a 10 keV threshold (dash-dotted); XENON100 with constant (+) or decreasing (□) scintillation-efficiency extrapolations at low energy; DAMA/LIBRA signal regions (dark fill); CoGeNT 2011 (light fill); and combined fit to DAMA/LIBRA and CoGeNT data (hatched). Additional SD limits shown include: CDMS II Ge results with a 10 keV threshold (dash-dotted); XENON10 (△); CRESST (○); and 99.7% DAMA/LIBRA allowed region for neutron-only scattering.

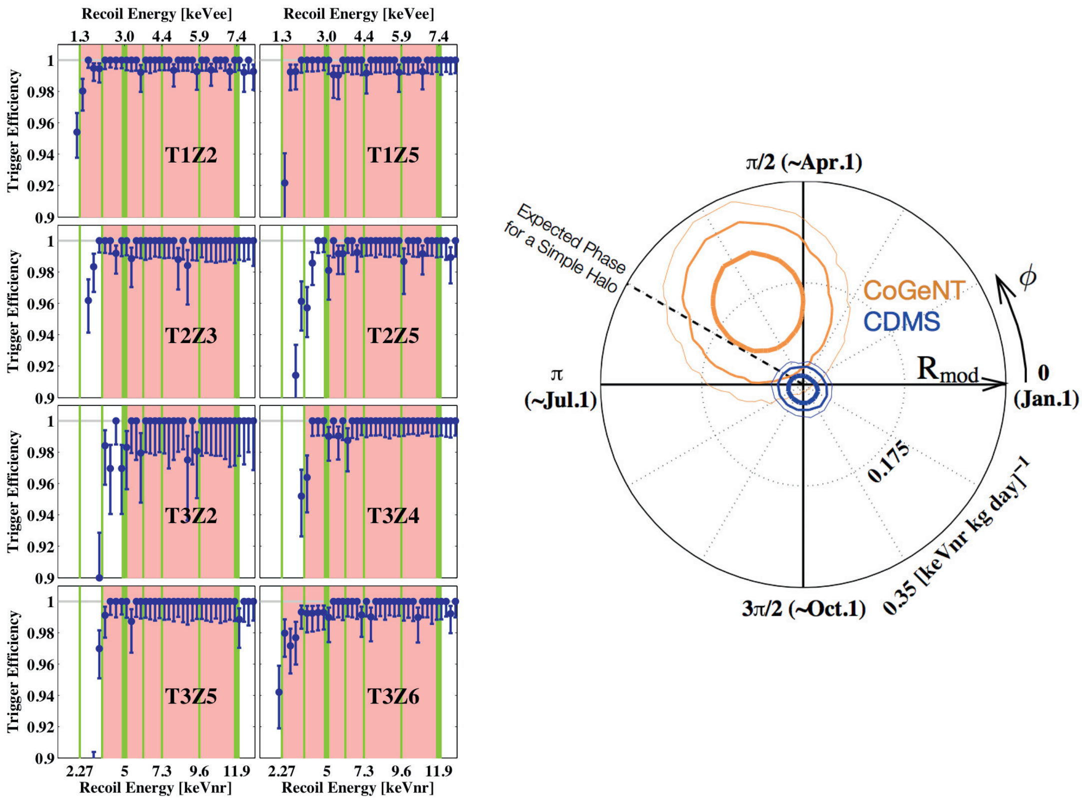

Fig. 4. Right: Trigger efficiency versus recoil energy for the eight low-threshold germanium detectors selected for the low threshold germanium analysis and the search for annual modulation as shown in [16]. The pink background shading indicates the range over which the detector was used during the annual modulation analysis. Left: 68%, 95%, and 99% confidence intervals of modulation amplitude for CoGeNT (2011, [9]) (shown in orange) and CDMS II (blue). Figure from [16]. CoGeNT has since released an update to their analysis spanning its total 3.4 year run [10].

at the 99% confidence level. A comparison with the 2011 analysis of the three-year CoGeNT data set disfavored a WIMP interpretation of the reported CoGeNT modulation between 1.2-3.2 keV electron equivalent at >98% confidence (see Figure 4).

Results of extension of the modulation analysis below 5 keV_{nr} to the 2.27 keV_{nr} threshold of the germanium analysis, which also overlaps a large portion of the energy range covered by the CoGeNT experiment, is the subject of pending publication.

4. Systematics in the search for annual modulation

Both the extension of the analysis to lower thresholds and a full grasp of the implications for other experiments probing the same region require a deeper understanding of the systematics at low energies and of the potential for systematic effects to mimic a WIMP signal in its absence, or mask the presence of a modulating signal that could be attributed, at least in part, to the presence of WIMP dark matter. Two scenarios are of primary concern. The first scenario is the case in which a periodic background signal mimics the behavior of an annually modulating WIMP signal with a compatible period, phase, and amplitude, causing a false or distorted detection signal. Several authors (see, for example [3]) have shown that more realistic dark matter halo models can cause shifts in the expected amplitude and phase of a WIMP signal, enhancing the parameter space for WIMPs and making it more difficult to rule out signals based solely on those parameters. The second scenario is the case of a background modulation signal that is out of phase

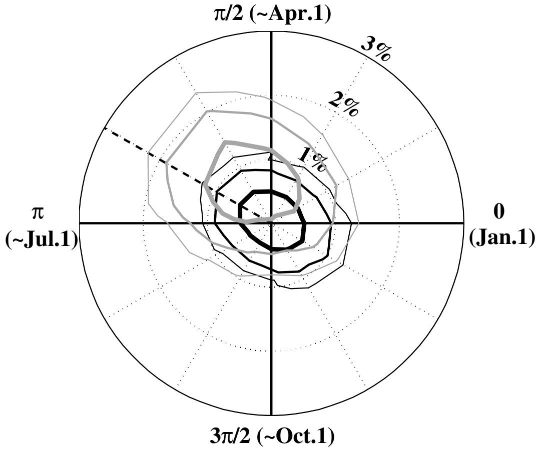

Fig. 5. 68%, 95%, and 99% confidence intervals for phase and amplitude of relative efficiency modulation of the fiducial volume and signal region cuts. The dashed line shows the preferred phase for the standard halo model (152.5 days). Figure from [16].

with an actual WIMP signal. In this case, the destructive interference of the two signals can effectively cancel any modulation, yielding a null result where a signal should be present. Both scenarios can be dangerous in experiments where backgrounds are poorly understood or even unknown. While there are a number of potential contributors to the systematic effects of any experiment, we identify and investigate three dominant effects: time-varying signal efficiencies, time-varying background-acceptance by the signal region, and modulating background event rates. Understanding the magnitude and nature of any time-varying systematics is crucial to the identification or exclusion of a WIMP dark matter signal.

4.1. Signal acceptance efficiency

Events selected for the modulation analysis were required to have ionization energies consistent with noise in the outer charge electrode (fiducial volume cut), and an ionization yield within 2-sigma of the mean of the nuclear recoil band (signal region cut) [16]. The application of each cut results in an efficiency $\varepsilon(t, E, d)$ that depends on the time, t, the deposited energy, E, and the detector d. The pre-selection (data quality) cuts possess negligible time dependence. For the fiducial volume and signal region cuts we place upper limits on any contribution to a modulating signal using a simplified approximation to the Feldman-Cousins approach [17, 18], in which we assume the asymptotic approximation for the likelihood ratio distributions. Figure 5 (bottom) shows the 68%, 95%, and 99% confidence levels of the relative amplitude and phase of annual modulation in the fiducial volume cut and in the signal region cut for the same energy range, 5-11.9 keV, as shown in figure 4. The 95% confidence level upper limit of 2% efficiency modulation shown in the figure is not sufficient to mask the CoGeNT maximum likelihood. A modulation of the magnitude of the maximum likelihood amplitude claimed by CoGeNT would have required a 100% modulation of the CDMS II candidate event sample over the range 5-11.9 keV_{nr}.

4.2. Cut acceptance of backgrounds

For each of the six runs included in the CDMS II search for annual modulation, the signal region (nuclear recoil band cut) was defined based on nuclear recoils from Cf-252 calibration data taken over the course of the run. In this study, we examine fluctuations in the acceptance of background events by the nuclear recoil yield band cut due to run-varying band definitions. Using the ionization distributions of "random" triggered events throughout CDMS II, and the measured recoil energy spectrum of zero charge events in the detectors, we generate a set of simulated "zero-yield" (i.e., ionization signal consistent with noise) events and study

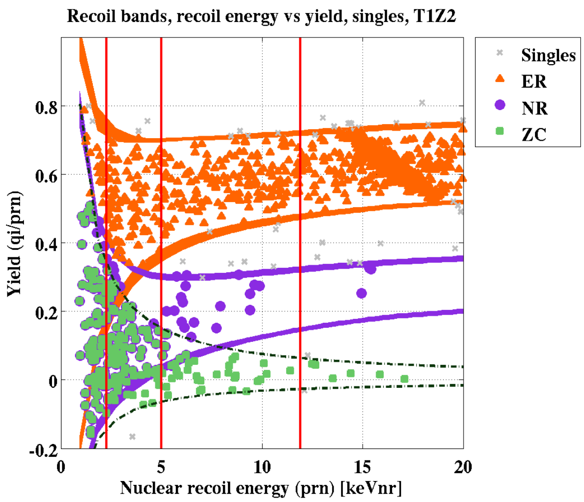

Fig. 6. Background yield regions in the CDMS II single-scatter WIMP-search data for detector T1Z2. Events falling into each band region are highlighted with the color of the band. Band widths are representative of varying band definitions from CDMS II. From the top: Gammas (orange triangles), nuclear recoils (purple circles), and zero-yield background events (green squares). Note the heavy overlap of the zero-yield band with the signal region below 5 keV_{nr}. The red lines show, from left to right, the 2.27, 5, and 11.9 keV_{nr} thresholds of the analysis.

the acceptance rates of this background as a function of time. Early indications suggested that contributions from this systematic are negligible.

4.3. Modulation of backgrounds

In order to quantify the maximum expected contribution of backgrounds, in particular zero-yield events, to a modulation in in the signal rate, we also study the amount of modulation present in the various yield regions of the WIMP-search data backgrounds throughout CDMS II. Additional regions of the WIMP-search background data under study are the multiple-scatter events and adjacent and overlapping gamma and zero-yield bands. Observations in these regions provide additional handles on the origins of time-varying changes in the data introduced by cuts or outside sources. Figure 6 shows, from top to bottom, the 1) gamma band, 2) surface events (gray points beneath gamma band), 3) nuclear recoil band (signal region), 4)(corner, left) overlap of the signal and zero-yield bands, and 5) the zero yield band. Modulation studies of the background regions will be detailed in a future publication.

5. Conclusion & Outlook

Dedicated low-threshold searches for nuclear recoil excess and signal modulation in CDMS II have reported results consistent with a background-only hypothesis, setting upper limits on the allowed interaction cross section and modulation spectrum for WIMPs of a given model. Below the currently published 5 keV_{nr} threshold, there is a significant overlap between the signal region and the population of zero-yield events known to provide one the most significant sources of background in the CDMS II experiment. In addition, the trigger efficiency of the detectors is reduced. In rare event searches, which often push the limits of detector capabilities and explore unknown regions of parameter space, a reliable understanding of the systematic errors becomes increasingly important. The Collaboration is currently working to release the results of extending the analysis to a lower threshold of 2.27 keV_{nr}, with an examination of the systematic effects present for the entire energy range. Effects from signal efficiency modulation have been shown minimal for this analysis, and additional results on background studies in and beyond the signal region will be presented in a subsequent publication.

6. Acknowledgements

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