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Silicon detector dark matter results from the final exposure of CDMS II

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We report results of a search for weakly interacting massive particles (WIMPs) with the silicon detectors of the CDMS II experiment. This blind analysis of 140.2 kg day of data taken between July 2007 and September 2008 revealed three WIMP-candidate events with a surface-event background estimate of $0.41^{+0.20}_{-0.08}$ (stat)$^{+0.28}_{-0.24}$ (syst). Other known backgrounds from neutrons and $^{206}$Pb are limited to $<0.13$ and $<0.08$ events at the 90% confidence level, respectively. The exposure of this analysis is equivalent to 23.4 kg day for a recoil energy range of 7–100 keV for a WIMP of mass $10 \text{ GeV}/c^2$. The probability that the known backgrounds would produce three or more events in the signal region is 5.4%. A profile likelihood ratio test of the three events that includes the measured recoil energies gives a 0.19% probability for the known-background-only hypothesis when tested against the alternative WIMP + background hypothesis. The highest likelihood occurs for a WIMP mass of $8.6 \text{ GeV}/c^2$ and WIMP-nucleon cross section of $1.9 	imes 10^{-41}$ cm$^2$.

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There is now overwhelming evidence that the bulk of the matter in our Universe is in some nonluminous, non-baryonic form [1]. Weakly interacting massive particles (WIMPs) [2] form a leading class of candidates for this dark matter. Particles of this type would be produced thermally in the early Universe and are predicted by many theoretical extensions to the standard model of particle physics [1,3,4]. If WIMPs do constitute the dark matter in our Galaxy, they may be detectable through their elastic scattering from nuclei in terrestrial particle detectors [5]. Numerous experimental groups have sought to detect such scattering events using a wide variety of technologies [6].

The Cryogenic Dark Matter Search (CDMS) Collaboration identifies nuclear recoils (including those that would occur in WIMP interactions) using semiconductor detectors operated at 40 mK. These detectors use simultaneous measurements of ionization and nonequilibrium phonons to identify such events among the far more numerous background of electron recoils.

The low atomic mass of Si generally makes it a less sensitive target for spin-independent WIMP interactions relative to the larger coherent enhancement of the scattering cross section for heavy nuclei. On the other hand, the lower atomic mass of Si is advantageous in searches for WIMPs of relatively low mass (≈10 GeV/c^2) due to more favorable scattering kinematics. New particles at such masses are generally disfavored in fits of models to precision electroweak data (e.g., Ref. [7]), but viable models in this regime do exist (e.g., Refs. [8,9]). Renewed interest in this mass range has been motivated by results from the DAMA/LIBRA [10], CoGeNT [11], and CRESST [12] experiments, which can be interpreted as evidence of low-mass WIMP scattering.

During 2003–2008 the collaboration operated CDMS II, an array of Ge and Si detectors located at the Soudan Underground Laboratory [13–19]. In its final configuration, the CDMS II array consisted of 30 Z-sensitive ionization and phonon (ZIP) detectors: 19 Ge (≈239 g each) and 11 Si (≈106 g each), for a total of 4.6 kg of Ge and 1.2 kg of Si. We discriminate nuclear recoils from background electron recoils using the ratio of ionization to phonon recoil energy (ionization “yield”). Electron recoils that occur within 10 μm of a detector surface can exhibit reduced ionization collection. These events are identified by phonon pulse-shape discrimination. Our overall misidentification rate of electron recoils is less than 1 in 10^6.

We consider data from the Si detectors using the final four run periods of the full CDMS II detector installation acquired between July 2007 and September 2008. The Ge results from this data set have been described in previous publications [17,20]. Compared to Si data from the earlier CDMS II runs described in Ref. [21], these data benefit from improved analysis and calibration techniques. Of the 11 Si detectors, three were excluded from the WIMP-search analysis: two due to wiring failures that led to incomplete collection of the ionization signal and one due to unstable response on one of its four phonon channels. Periods of poor performance, as identified by a series of Kolmogorov-Smirnov tests, were also excluded from analysis. After all such exclusions, the data collected by the eight Si detectors considered in this analysis represent a total exposure of 140.2 kg day prior to the application of the WIMP-candidate selection criteria.

The responses of these detectors to electron and nuclear recoils were calibrated using events from extensive exposures to 133Ba and 252Cf sources in situ at Soudan. Electron recoils from the former were used to empirically characterize and correct for the dependence of phonon pulse shape on event position and energy. The 356 keV gamma ray from the 133Ba source has a 4.2 cm attenuation length in Si, and thus the Si detectors generally do not show a clear line at 356 keV. Their energy scales were calibrated using 356 keV events with total energies shared between the Si detector and a neighboring detector.

WIMP-candidate events were identified by a series of selection criteria. All WIMP selection criteria were defined using calibration data plus WIMP search data in which events in and near the WIMP-candidate region were masked. Thus, WIMP candidates had no impact on the definition of the selection criteria. A WIMP candidate was required to have phonon and ionization signals above the noise in exactly one ZIP detector and to exhibit no coincident energy in the scintillating veto shield. Events in coincidence with the NuMI beam [22] were also vetoed. We demanded that any candidate event occur within the detector’s fiducial volume defined by requiring signal consistent with noise in the outer ionization electrode. The recoil energy of each candidate event had to lie below 100 keV and above a detector-dependent threshold ranging from 7 to 30 keV, chosen blindly using calibration data to keep the total expected leakage of bulk electron-recoil events into the nuclear-recoil band below 0.03 events. Candidate events were further required to lie >4.5σ above the ionization channel noise as measured by randomly acquired triggers for each detector during each contiguous period of data taking (∼24 h).

In yield, events were required to be within +1.2σ and -1.8σ from the mean of the nuclear-recoil yield. Candidate events were also required to have phonon pulse timing consistent with a nuclear recoil. In order to take advantage of the fact that the timing parameters are better measured at high energies, the phonon timing data-selection cut was optimized in three energy bins: 7–20, 20–30, and 30–100 keV [23]. Figure 1 shows the nuclear-recoil efficiency, i.e., the estimated fraction of nuclear recoils at a given energy that would be accepted by these signal criteria, measured using nuclear recoils from 252Cf calibration. The abrupt changes in efficiency are due to the different detector thresholds and changes to the timing cuts in the three energy bins. Signal acceptance was measured using nuclear recoils from 252Cf calibration. After applying
A greater source of background is the misidentification of surface electron recoils, which may suffer from reduced ionization yield and thus contribute events to the WIMP-search sample. Classical confidence intervals provided similar estimates [26].

After unblinding, extensive checks of the three candidate events revealed no data quality or analysis issues that would invalidate them as WIMP candidates. The signal to noise on the ionization channel for the three events (ordered in increasing recoil energy) was measured to be $6.7\sigma$, $4.9\sigma$, and $5.1\sigma$. A study on possible leakage into the signal band due to $^{208}\text{Pb}$ recoils from $^{210}\text{Po}$ decays found the expected leakage to be negligible with an upper limit of $<0.08$ events at the $90\%$ confidence level. The energy distribution of the $^{208}\text{Pb}$ background was constructed using events in which a coincident $\alpha$ particle was detected in a detector adjacent to one of the eight Si detectors used in this analysis.
This result constrains the available parameter space of WIMP dark matter models. We compute upper limits on the WIMP-nucleon scattering cross section using Yellin’s optimum interval method [27]. We assume a WIMP mass density of 0.3 GeV/c^2/cm^3, a most probable WIMP velocity with respect to the Galaxy of 220 km/s, a mean circular velocity of Earth with respect to the Galactic center of 232 km/s, a Galactic escape velocity of 544 km/s [28], and the Helm form factor [29]. The effect of an annual modulation of the 10 GeV/c^2 WIMP rate found by integrating over the specific data-taking periods for this analysis with the above assumptions introduces a \(<2\% shift downward in the cross sections of our results and is thus neglected. Figure 4 shows the derived upper limits on the spin-independent WIMP-nucleon scattering cross section at the 90\% C.L. from this analysis and a selection of other recent results. The present data set an upper limit of 2.4 \times 10^{-41} \text{cm}^2 for a WIMP of mass 10 GeV/c^2. We are completing the calibration of the nuclear-recoil energy scale using the Si-neutron elastic scattering resonant feature in the ^{252}\text{Cf} exposures. This study indicates that our reconstructed energy may be 10\% lower than the true recoil energy, which would weaken the upper limit slightly. Below 20 GeV/c^2, the change is well approximated by shifting the limits parallel to the mass axis by \(\sim 7\%\), making the limits weaker at low masses. In addition, neutron calibration multiple-scattering effects improve the response to WIMPs, thus shifting the upper limit down to a lower cross-section axis and making the limits stronger by \(\sim 5\%\).
A model of our known backgrounds including both energy and expected rate distributions was constructed for each detector and experimental run for each of the three backgrounds considered: surface electron recoils, neutron backgrounds, and $^{208}$Pb recoils. Simulations of our background model yield a 5.4% probability of a statistical fluctuation producing three or more events in our signal region.

This model of our known backgrounds was used to investigate the data in the context of a WIMP + background hypothesis. We performed a profile likelihood analysis, including the event energies, in which the background rates were treated as nuisance parameters and the WIMP mass and cross section were the parameters of interest. We profiled over probability distribution functions of the rate for each of our known backgrounds. The highest likelihood was found for a WIMP mass of 8.6 GeV/c$^2$ and a WIMP-nucleon cross section of $1.9 \times 10^{-41}$ cm$^2$. The goodness-of-fit test of this WIMP + background hypothesis results in a $p$ value of 68%, while the background-only hypothesis fits the data with a $p$ value of 4.5%. A profile likelihood ratio test finds that the data favor the WIMP + background hypothesis over our background-only hypothesis with a $p$ value of 0.19%. Though this result favors a WIMP interpretation over the known-background-only hypothesis, we do not believe this result rises to the level of a discovery.

Figure 4 shows the resulting best-fit region from this analysis (68% and 90% confidence level contours) on the WIMP-nucleon cross section versus WIMP mass plane. The 90% C.L. exclusion regions from CDMS II’s Ge and Si analyses and EDELWEISS low-threshold analysis cover part of this best-fit region, but the results are overall statistically compatible. While there is some tension with the upper limits from the XENON10 experiment, the XENON100 experiment significantly constrains this parameter space under standard assumptions about the WIMP velocity distribution and WIMP-nucleus interactions. Additional, planned studies of these CDMS II Si data with reduced threshold may provide additional insight into a WIMP interpretation of these data. Future experiments with Si-based detectors that would be sensitive to WIMPs in this region of parameter space are also under consideration by the SuperCDMS Collaboration.

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