

**First Results from the Cryogenic Dark Matter Search in the Soudan Underground Laboratory**

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We report the first results from a search for weakly interacting massive particles (WIMPs) in the Cryogenic Dark Matter Search experiment at the Soudan Underground Laboratory. Four Ge and two Si detectors were operated for 52.6 live days, providing 19.4 kg d of Ge net exposure after cuts for recoil energies between 10 and 100 keV. A blind analysis was performed using only calibration data to define the energy threshold and selection criteria for nuclear-recoil candidates. Using the standard dark-matter halo and nuclear-physics WIMP model, these data set the world's lowest exclusion limits on the coherent WIMP-nucleon scalar cross section for all WIMP masses above 15 GeV/ $c^2$ , ruling out a significant range of neutralino supersymmetric models. The minimum of this limit curve at the 90% C.L. is  $4 \times 10^{-43}$  cm<sup>2</sup> at a WIMP mass of 60 GeV/ $c^2$ .

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There is a compelling scientific case that nonluminous, nonbaryonic, weakly interacting massive particles (WIMPs) [1–3] may constitute most of the matter in the Universe [4]. Supersymmetry provides a natural WIMP candidate in the form of the lightest superpartner, which must be stable if  $R$  parity is conserved [5–9]. The WIMPs are expected to be in a roughly isothermal halo whose gravitational potential well contains the visible portion of our galaxy. These WIMPs would interact elastically with nuclei, generating a recoil energy of a few tens of keV, at a rate smaller than  $\sim 1$  event kg<sup>-1</sup> d<sup>-1</sup> [2,3,5–10].

The Cryogenic Dark Matter Search (CDMS) Collaboration is searching for WIMPs with a new apparatus [11] in the Soudan Underground Laboratory. The CDMS Soudan experiment, also called CDMS II, uses a set of Ge (each 250 g) and Si (each 100 g) ZIP

( $Z$ -dependent ionization and phonon) detectors [12], cooled to a temperature  $< 50$  mK and surrounded by substantial shielding deep underground to reduce backgrounds from radioactivity and cosmic-ray interactions. Simultaneous measurement of ionization and athermal phonon signals in the Ge and Si detectors allows excellent rejection of the remaining gamma and beta backgrounds. These background particles scatter off electrons in the detectors, while WIMPs (and neutrons) scatter off nuclei. The ZIP detectors allow discrimination between electron and nuclear recoils through two effects. First, for a given energy, recoiling electrons are more ionizing than recoiling nuclei, resulting in a higher ratio of ionization to phonon signal, called “ionization yield.” Second, the athermal phonon signals due to nuclear recoils have longer rise times and occur later than those due to electron recoils. For recoils within a few  $\mu\text{m}$  of a detector's

surface (primarily from low-energy electrons), the charge collection is incomplete [13], making discrimination based on ionization yield less effective. But these events can be effectively rejected by phonon-timing cuts because they have, on the average, even faster phonon signals than those from bulk electron recoils [14,15]. These effects are in qualitative agreement with our understanding of the complex phonon and semiconductor physics involved [16].

The detectors are surrounded by an average of 0.5 cm of copper, 22.5 cm of lead, and 50 cm of polyethylene, which reduce backgrounds from external photons and neutrons. A 5-cm-thick scintillator muon veto enclosing the shielding identifies charged particles (and some neutral particles) that pass through it. An overburden of 780 m of rock, or 2090 meters water equivalent (mwe), reduces the surface muon flux by a factor of  $5 \times 10^4$ .

All materials surrounding the detectors have been screened to minimize radioactive decays which could produce neutrons. Neutrons resulting from radioactive decays outside the shield are moderated sufficiently to produce recoil energies below our detector threshold. Neutrons produced in the shield by high-energy cosmic-ray muons are tagged by the veto scintillator with an efficiency  $>99\%$ . The dominant unvetoes neutron background is expected to arise from neutrons produced by cosmic-ray muon interactions in the walls of the cavern. Events due to neutrons can be distinguished in part from ones due to WIMPs because neutrons often scatter in more than one detector and interact at about the same rate in Si and Ge. By contrast, WIMPs would not multiple scatter, and coherent scalar WIMP interactions would occur  $\sim 6$  times more often in Ge than in Si detectors.

We report here the analysis of the first CDMS Ge WIMP-search data taken at Soudan during the period 11 October 2003 through 11 January 2004 [11]. After excluding time for calibrations, cryogen transfers, maintenance, and periods of increased noise, we obtained 52.6 live days with the four Ge and two Si detectors of “Tower 1” [six close-stacked ZIP detectors labeled as Z1(Ge), Z2(Ge), Z3(Ge), Z4(Si), Z5(Ge), and Z6(Si) from top to bottom]. Tower 1 was operated previously in an identical configuration at the Stanford Underground Facility (SUF), at a depth of 17 mwe [17].

Energy calibrations were performed repeatedly during the run using a  $^{133}\text{Ba}$  gamma source with distinctive, penetrating lines at 356 and 384 keV. The excellent agreement between data and Monte Carlo simulations and the observation of the 10.4 keV Ga line from neutron activation of Ge indicated that the energy calibration was accurate and stable to within a few percent. Observation of the predicted energy spectrum from a  $^{252}\text{Cf}$  source confirmed the energy scale for nuclear recoils [11].

The trigger rate on phonon signals for the WIMP-search data runs was  $\sim 0.1$  Hz, with a recoil-energy

threshold of  $\sim 2$  keV ( $\sim 4$  keV for Z1). The muon veto signals were recorded in a time history buffer for each detector trigger. The summed veto rate above threshold was  $\sim 600$  Hz, mainly due to ambient gammas. At this rate, we reject about 3% of events with accidental veto coincidences in the  $50 \mu\text{s}$  before a detector trigger. Data-quality cuts reject the  $\sim 5\%$  of events that show any sign of higher pretrigger noise or possible pileup.

We performed a blind analysis in which the nuclear-recoil region for the WIMP-search data was not inspected until all cuts and analysis thresholds were defined using *in situ* gamma and neutron calibrations (see Fig. 1). A combination of ionization-yield and phonon-timing cuts rejects virtually all calibration electron recoils while accepting most of the nuclear recoils. The phonon-timing cuts are based on both the phonon rise time and the phonon start time relative to the ionization signal (see Fig. 2). We required recoil energy between 10 and 100 keV for all Ge detectors except Z1, whose larger noise required an analysis threshold of 20 keV in order to ensure comparable rejection. We rejected events with some ionization in a detector’s annular “guard” electrode, which covers 15% of the detector’s volume. Figure 3 shows a conservative estimate of the combined efficiency of all cuts on a WIMP signal. The cuts yield a spectrum-

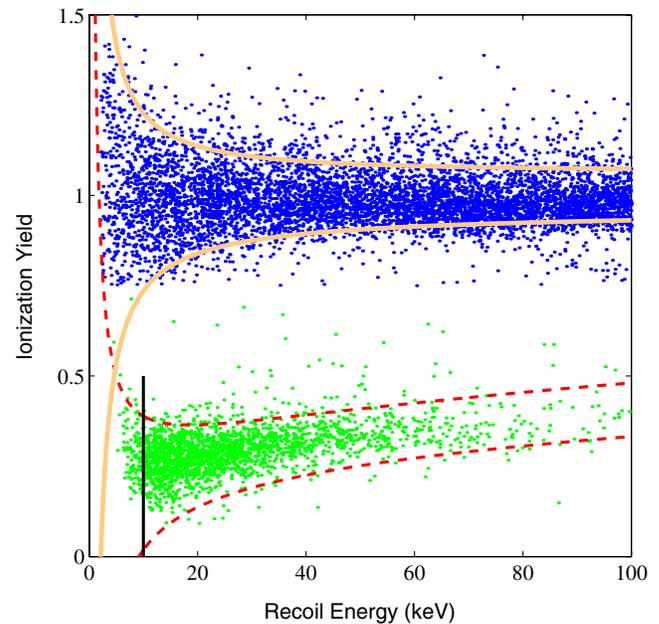


FIG. 1 (color online). Ionization yield versus recoil energy for calibration data with a  $^{252}\text{Cf}$  gamma and neutron source for detectors Z2, Z3, and Z5 in Tower 1 showing the  $\pm 2\sigma$  gamma band (solid curves) and the  $\pm 2\sigma$  nuclear-recoil band (dashed curves) for Z5, the detector with the worst noise of these three. Events with ionization yield  $< 0.75$  (gray) are shown only if they pass the phonon-timing cuts. The vertical line is the 10 keV analysis threshold for these three detectors.

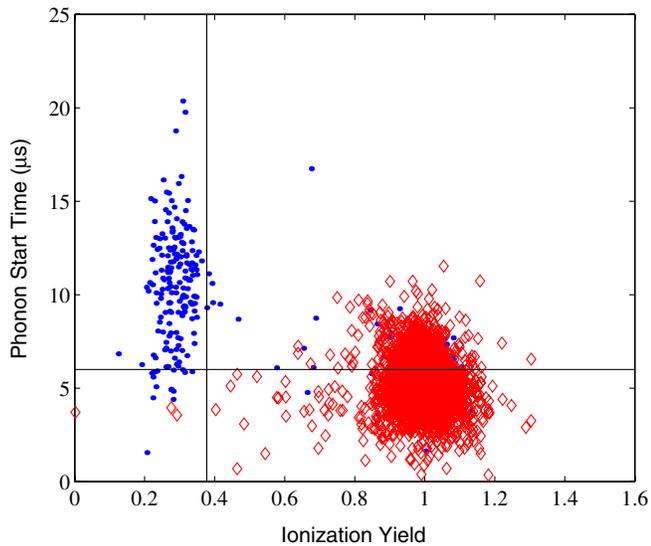


FIG. 2 (color online). Phonon start time versus ionization yield for  $^{133}\text{Ba}$  gamma-calibration events (diamonds) and  $^{252}\text{Cf}$  neutron-calibration events (dots) in the energy range 20–40 keV in detector Z5 in Tower 1. Lines indicate typical timing and ionization-yield cuts, resulting in high nuclear-recoil efficiency and a low rate of misidentified surface events.

averaged effective exposure of 19.4 kg d between 10 and 100 keV for a  $60 \text{ GeV}/c^2$  WIMP.

Table I lists the observed rates of unvetoed events in the WIMP-search data, with ionization yield either in the  $\pm 2\sigma$  gamma band (“gammas”) or below this band (mostly surface-electron recoils). Analysis shows that about half the surface-electron recoils with interactions in only a single detector (“singles”) were due to beta decays of contaminants on surfaces, while the other half were from gamma rays. Gamma rates are  $\sim 50\%$  higher at Soudan than they were at SUF, consistent with the higher Rn levels at Soudan and the absence of a 1-cm-thick ancient-Pb liner which surrounded the detectors at SUF. Total surface-event rates at Soudan are also somewhat

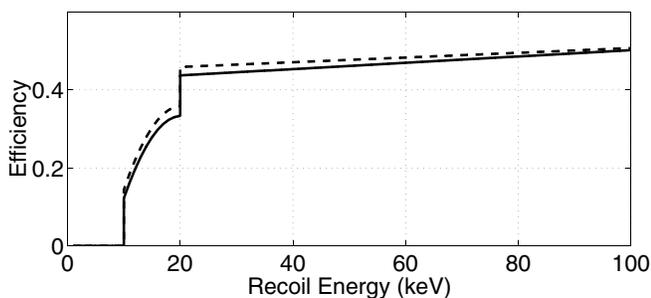


FIG. 3. Efficiency of the combined cuts as a function of recoil energy, both for the blind analysis (solid line) and for the second, nonblind analysis (dashed line). The step at 20 keV is due to Z1’s 20-keV analysis threshold.

TABLE I. Unvetoed gamma and surface-electron-recoil rates between 15 and 45 keV in Tower 1 at Soudan.

ZIP	Gammas (No./kg/d)		Surface (No./d)	
	(Total)	(Singles)	(Total)	(Singles)
Z1(Ge)	$85.6 \pm 3.4$	$37.6 \pm 2.3$	$1.56 \pm 0.23$	$0.90 \pm 0.18$
Z2(Ge)	$79.4 \pm 3.1$	$19.7 \pm 1.6$	$1.05 \pm 0.18$	$0.18 \pm 0.08$
Z3(Ge)	$89.3 \pm 3.3$	$19.9 \pm 1.5$	$1.11 \pm 0.18$	$0.15 \pm 0.07$
Z5(Ge)	$105.7 \pm 3.6$	$35.9 \pm 2.1$	$1.82 \pm 0.24$	$0.65 \pm 0.14$

higher than at SUF, consistent with the increased component due to gammas.

We computed the number of electron-recoil events expected to be misidentified as nuclear recoils in the WIMP-search data based on the  $^{133}\text{Ba}$  calibration sets used to determine the timing cuts. Factoring in systematic errors, we estimated  $0.4 \pm 0.3$  misidentified events in Z1 and a total of  $0.3 \pm 0.2$  in the other Ge detectors. As a check, we applied the same cuts to a different set of  $^{133}\text{Ba}$  calibrations, containing 1.5 times as many surface events as in the WIMP-search data. One event (at 50 keV in Z1) passed all cuts, in agreement with the previous estimate.

Monte Carlo simulations predict  $0.05 \pm 0.02$  neutrons (mostly unvetoed) produced from muon interactions out-

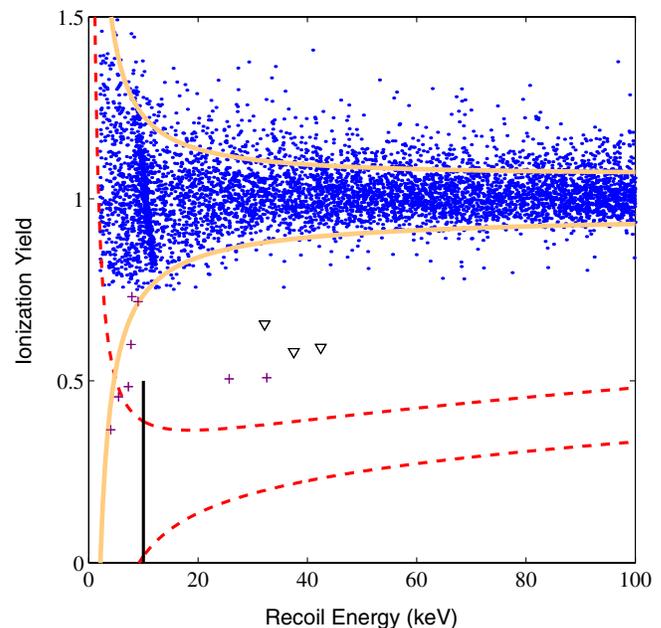


FIG. 4 (color online). Ionization yield versus recoil energy for WIMP-search data from Z2 (triangles), Z3, and Z5 (+) in Tower 1, using the same yield-dependent cuts and showing the same curves as in Fig. 1. Above an ionization yield of 0.75, the events from all three detectors are drawn as identical points in order to show the 10.4 keV Ga line from neutron activation of Ge.

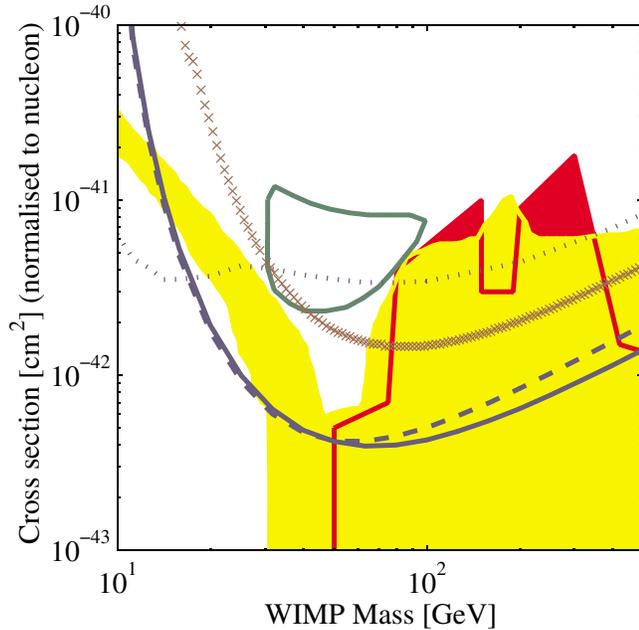


FIG. 5 (color online). New limit on the WIMP-nucleon scalar cross section from CDMS II at Soudan with no candidate events in 19.4 kg d effective Ge exposure (solid curve). Parameter space above the curve is excluded at the 90% C.L. These limits constrain supersymmetry models, for example, [8] (dark gray) and [9] (light gray). The DAMA (1–4)  $3\sigma$  signal region [18] is shown as a closed contour. Also shown are limits from CDMS at SUF [17] (dotted curve), EDELWEISS [19] ( $\times$ 's), and the second, nonblind analysis of CDMS II at Soudan with one nuclear-recoil candidate event (dashes). All curves [20] are normalized following [10], using the Helm spin-independent form factor,  $A^2$  scaling, WIMP characteristic velocity  $v_0 = 220 \text{ km s}^{-1}$ , mean Earth velocity  $v_E = 232 \text{ km s}^{-1}$ , and  $\rho = 0.3 \text{ GeV } c^{-2} \text{ cm}^{-3}$ .

side the shielding, including uncertainties on the neutron production rate. The simulations predict  $\sim 1.9$  (veto-coincident) neutrons produced inside the shielding for the WIMP-search data. No veto-coincident nuclear-recoil candidates were observed in the WIMP-search data.

This blind analysis of the first Soudan CDMS II WIMP-search data set revealed no nuclear-recoil events in 52.6 kg d raw exposure in our Ge detectors. Figure 4 displays the ionization yield of WIMP-search events in Z2, Z3, and Z5 which passed the same cuts applied to calibration data in Fig. 1. As shown in Fig. 5, these data together with corresponding data for Z1 set an upper limit on the WIMP-nucleon cross section of  $4 \times 10^{-43} \text{ cm}^2$  at the 90% C.L. at a WIMP mass of  $60 \text{ GeV}/c^2$  for coherent scalar interactions and a standard WIMP halo.

After unblinding the nuclear-recoil region, we found that our pulse-fitting algorithm designed to handle saturated pulses had been inadvertently used to analyze most of the unsaturated pulses in the WIMP-search data. This

algorithm gives slightly worse energy resolution than the intended algorithm. The limit in Fig. 5 based on the blind analysis (solid line) correctly accounts for this effect. We have also performed a second, nonblind analysis, using the intended pulse-fitting algorithm and the same blind cuts, resulting in a 5% higher WIMP detection efficiency. This analysis resulted in one nuclear-recoil candidate (at 64 keV in Z5), consistent with the expected surface-event misidentification quoted above. Figure 5 includes the optimum interval [21] limit based on this second unbiased, but nonblind, analysis (dashed line).

At  $60 \text{ GeV}/c^2$ , these limits are a factor of 4 below the best previous limits set by EDELWEISS [19], and a factor of 8 better than our limit with the same Tower 1 at SUF [17]. These data confirm that events detected by CDMS at SUF and those detected by EDELWEISS were not a WIMP signal. Under the assumptions of a standard halo model, our new limits are clearly incompatible with the DAMA (1–4) signal region [18] if it is due to coherent scalar WIMP interactions (for DAMA regions under other assumptions, see [22]). Our new limits significantly constrain supersymmetric models under some theoretical frameworks that place weak constraints on symmetry-breaking parameters (e.g., [7–9]).

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