Dark Matter Search Results from the CDMS II Experiment

The CDMS II Collaboration*†

Astrophysical observations indicate that dark matter constitutes most of the mass in our universe, but its nature remains unknown. Over the past decade, the Cryogenic Dark Matter Search (CDMS II) experiment has provided world-leading sensitivity for the direct detection of weakly interacting massive particle (WIMP) dark matter. The final exposure of our low-temperature germanium particle detectors at the Soudan Underground Laboratory yielded two candidate events, with an expected background of 0.9 ± 0.2 events. This is not statistically significant evidence for a WIMP signal. The combined CDMS II data place the strongest constraints on the WIMP-nucleon spin-independent scattering cross section for a wide range of WIMP masses and exclude new parameter space in inelastic dark matter models.

A wide variety of observational evidence (1) indicates that ~85% of the matter in our universe is in some nonluminous form that has thus far eluded laboratory identification. The inferred properties of this dark matter suggest that it is composed of elementary particles beyond those described in the Standard Model of particle physics, weakly interacting massive particles (WIMPs) (2) are a class of candidates to constitute this dark matter that are particularly well-motivated by independent considerations of cosmology and particle physics (3–5). If WIMPs constitute the dark matter in our galaxy, they should occasionally scatter elastically off atomic nuclei in a terrestrial target (6, 7). Laboratory searches for such scattering events (8–10) establish their rate to be less than 0.1 per day per kilogram of target mass, and researchers have begun to test the most interesting classes of WIMP models.

The Cryogenic Dark Matter Search (CDMS II) experiment seeks to detect recoiling atomic nuclei (nuclear recoils) from WIMP-scattering events using particle detectors operated at cryogenic temperatures (~50 mK) (8, 11). Each detector is a semiconductor disk ~10 mm thick and 76 mm in diameter, which is photolithographically patterned with sensors to detect the phonons and ionization generated by incident particles. These detectors have extraordinary power to distinguish nuclear recoils (produced by interactions of WIMPs or neutrons) from the far more common electron recoils produced by incident photons and electrons. Nuclear recoils generate less ionization than electron recoils of the same deposited energy, allowing event-by-event rejection of electron-recoil events with a misidentification rate of ~1 in 10⁶. Electron recoils within a few μm of the detector surface can suffer from reduced ionization collection, but these may be identified by the relatively fast arrival of their phonon signals. Combining the ratio of ionization to phonon recoil energy (ionization yield) with the timing of the phonon signals gives an overall misidentification rate of <1 in 10⁻⁶ for electron recoils.

CDMS II operated an array of 30 such detectors (19 Ge and 11 Si) in a low-radioactivity installation in the Soudan Underground Laboratory, Minnesota, USA (11). The depth of the experimental facility (713 m below the surface) greatly reduces the rate of background events from particle showers induced by cosmic rays. Nearly all remaining events from this source were identified using a layer of plastic scintillator surrounding the detector volume. Inner layers of lead and polyethylene further shielded the detectors against environmental radioactivity. Data taken during four periods of stable operation between July 2007 and September 2008 were analyzed for this work. Because of their greater sensitivity to spin-independent WIMP scattering, only Ge detectors were used to search for WIMP scatters. After excluding periods of poor detector performance, a total exposure to WIMPs of 612 kg-days was considered for this work.

After detector calibration, we defined a series of criteria to identify candidate WIMP-scattering events. WIMP candidates were required to deposit 10 to 100 keV of energy in a single detector, have the ionization and phonon characteristics of a nuclear recoil, and have no identifiable energy deposition in the rest of the array or in the scintillator shield. These criteria are described in more detail in the supporting online material (SOM) text. To avoid unconscious bias, we performed a “blind analysis” in which the exact selection criteria were defined without prior knowledge of the content of the signal region or its vicinity. The fraction of nuclear recoil events accepted by these criteria was measured using a calibration sample of nuclear recoil events induced by a ²⁵²Cf source. Despite the great discrimination power of this experiment, a small expected rate of misidentified background events remains. In the exposure considered here, we expected to misclassify 0.8 ± 0.1 (statistical) ±0.2 (systematic) surface electron recoils as WIMP candidates. We also expect neutrons produced by cosmic rays and radioactivity to generate an average of ~0.1 nuclear recoils, which would be indistinguishable from WIMP scatters.

After finalizing all selection criteria, we “unblinded” to examine the contents of the WIMP acceptance region (SOM text). We observed two candidate events at recoil energies of 12.3 keV and 15.5 keV (Figs. 1 and 2). These events

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Fig. 2. Normalized ionization yield (number of standard deviations from the mean nuclear recoil yield) versus normalized timing parameter (timing relative to acceptance region) for events consistent with all signal criteria, excluding yield and timing. The top (bottom) plot shows events for detector T1Z5 (T3Z4) (see SOM text for detector nomenclature). Events with phonon timing characteristics consistent with our selection criteria are shown with round markers. The solid red boxes indicate the signal regions. The candidate events are the round markers inside the signal regions. The blue histograms indicate the distributions of calibration neutrons along each axis for the respective detector.

Fig. 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. The red (upper) solid line shows the limit obtained from the exposure analyzed in this work. 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. Previous results from CDMS (8), XENON10 (9), and ZEPLIN III (10) are shown for comparison. The shaded regions indicate allowed parameter space calculated from certain minimal supersymmetric models (17, 18).

Fig. 4. The shaded blue region represents WIMP masses and mass splittings for which there exists a cross section compatible with the DAMA/LIBRA (14) modulation spectrum at 90% confidence level under the inelastic dark matter interpretation (23). Excluded regions for CDMS II (solid-black hatched) and XENON10 (19) (red-dashed hatched) were calculated in this work using the optimum interval method.

References and Notes
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12. We calculate the 90% confidence level upper limit based on standard galactic halo assumptions (15) and in the presence of two events at the observed energies. We use the optimum interval method (26) with no background subtraction. A combined limit was also calculated by combining these data with all previous results from Soudan (8), including all candidates and with efficiency weighted by the exposure of each analysis. The abrupt features in these curves are consequences of threshold crossings at which intervals containing one or more events could enter into the optimum interval computation. An improved estimate of our detector mass was used for the reported exposure calculation and applied retroactively to our previous CDMS II result.
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The striking consequences of correlations in many-body systems. We report on an isentropic effect in a spin mixture of attractively interacting fermionic atoms in an optical lattice. As we adiabatically increase the control and manipulation of neutral atoms in optical lattices, we consider the case of an unpolarized system with corresponding to the two hyperfine states. We consider an attractively interacting spin Hubbard model. which occurs in the liquid-to-solid transition of $^3$He. As a result of its randomly oriented spins, the solid is more disordered than the liquid. When adiabatically squeezed, the liquid therefore freezes into a solid by absorbing heat. Recently, the extraordinary progress in the control and manipulation of neutral atoms in optical lattices ($5$–$7$) has added a valuable degree of freedom to the investigation of strongly correlated systems. By varying a collection of parameters such as scattering length, lattice depth, and external confinement, it is possible to adiabatically bring a weakly interacting gas of bosonic (7) or fermionic atoms (8–11) into a regime of strong correlations. The versatility of these systems makes them ideal candidates not only to simulate strongly correlated many-body phases, but also to investigate intriguing thermodynamic effects. In particular, the simulation and investigation of the single-band attractive fermionic Hubbard model has received special interest (12–16), both as a means of accessing the preformed-pair or pseudogap regime (12–15) and as an alternative route to study the physics of the repulsive Hubbard model (16), possibly providing insight into the origin of high-temperature superconductivity in cuprates (17, 18).

We consider an attractively interacting spin mixture of fermionic atoms in two distinct hyperfine states loaded into the lowest band of a three-dimensional (3D) optical lattice and placed in an external harmonic potential. Its physics can be described by a Hubbard Hamiltonian with an additional harmonic confining term:

$$H = -t \sum_{\langle i, j \rangle, \sigma} c_{i \sigma}^\dagger c_{j \sigma} + U \sum_i n_{i \uparrow} n_{i \downarrow} + E_c \sum_{i \alpha} r_{i \alpha} \dot{n}_{i \alpha}$$

where $c_{i \sigma}$, $c_{i \sigma}^\dagger$, and $n_{i \sigma}$ are, respectively, the fermionic annihilation operator, the fermionic creation operator, and the particle number operator at lattice site $\ell$ (with dimensionless coordinates $x$, $y$, and $z$), and spin state $\sigma \in \{\uparrow, \downarrow\}$, corresponding to the two hyperfine states. We consider the case of an unpolarized system with $N_\sigma = N/2$, where $N_\sigma$ is the number of particles per spin component and $N$ is the total number of particles. The Hamiltonian (Eq. 1) consists of three competing terms. The first term accounts for the kinetic energy of the system, which is characterized by the hopping amplitude $t$ between neighboring lattice sites; the second term describes the attractive on-site interaction $U < 0$ between atoms with opposite spin (Fig. 1A). The last term represents the confinement energy due to the external anisotropic harmonic potential. The characteristic energy $E_c = V_{r}$ is the mean potential energy per particle and spin state of a maximally packed shell at the bottom of the trap, where $r_{i \alpha}^2$ is the corresponding mean squared radius, $V_{r} = \frac{1}{2} \frac{m \omega_{r}^2}{\hbar^2} \frac{\hbar}{\omega_{r}} \frac{\omega_{r}}{\omega_{v}}$ [where $\omega_{r}$ are the horizontal trap frequencies and $\omega_{v}$ is the vertical trap frequency], and $m$ is the mass of

Anomalous Expansion of Attractively Interacting Fermionic Atoms in an Optical Lattice

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The interplay of thermodynamics and quantum correlations can give rise to counterintuitive phenomena in many-body systems. We report on an isentropic effect in a spin mixture of attractively interacting fermionic atoms in an optical lattice. As we adiabatically increase the adiabaticity the attraction between the atoms, we observe that the gas expands instead of contracting. This unexpected behavior demonstrates the crucial role of the lattice potential in the thermodynamics of the fermionic Hubbard model.
ERRATUM

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Reports: “Dark matter search results from the CDMS II experiment” by The CDMS II Collaboration (26 March, p. 1619). In the last sentence of the second paragraph, 10^{-6} should be 10^6.