2 Search for Cold Dark Matter with CDMS-II

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(CDMS-II Collaboration)

The Cryogenic Dark Matter Search (CDMS) experiment searches for Weakly Interacting Massive Particles (WIMPs), which are leading candidates for the non-baryonic matter in our Universe. The experiment has been operating successfully in a low-background facility at the Soudan Underground Laboratory since October 2003, and has delivered the world's best limits on the direct detection of WIMPs (1; 2).

At the experiment's core are Z(depth)-sensitive ionization and phonon-mediated (ZIP) detectors, which are cylindrical high-purity Ge (250 g) or Si (100 g) crystals kept at a base temperature of ∼40 mK. A particle interacting in a ZIP detector causes an electron or a nuclear recoil, depositing its energy into the crystal through charge excitations (electron-hole pairs) and lattice vibrations (phonons). The charge excitations are drifted in a low field (3V/cm) and collected with electrodes on the two sides of the ZIP detector. The phonon signal is detected by quasiparticle-trap electrothermal-feedback transition-edge sensors photolithographically patterned onto one of the crystal faces. Nuclear recoils produce less electron-ion pairs than electron recoils, thus the ionization yield, defined as $y = E_{charge}/E_{recoil}$, is smaller for nuclear recoils ($y \sim 0.3$ for Ge and ~ 0.25 for Si) than for electron recoils ($y = 1$) of the same energy. It provides the technique to reject the electron-recoil events which produce most of the background. A picture of the inner CDMS cryostat is shown in Fig. 2.1. A detailed description of the CDMS apparatus and shield is given in (2).

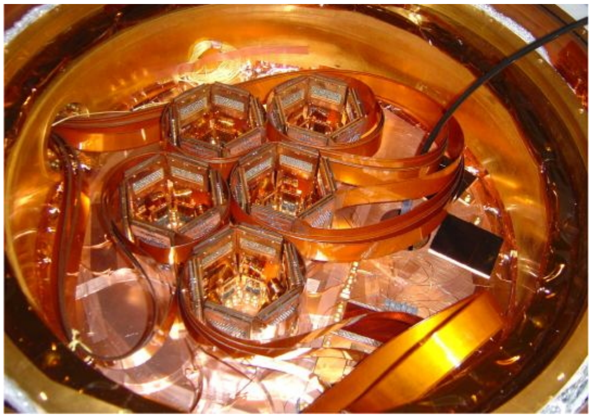

Figure 2.1: Open CDMS copper cryostat, showing the top of the 5 tower structures containing the field efect transistor cards for the ionization and the SQUID cards for the phonon readout, as well as the Cu kapton striplines which are used to carry the signals to room temperatures. Each tower contains 6 ZIP detectors (not seen here).

2.1 Analysis of the CDMS WIMP search runs

The CDMS-II experiment is operating five towers (19 Ge and 11 Si ZIP detectors) with 4.5 kg of Ge and 1.1 kg of Si, in stable WIMP search mode since October 2006. The data acquired between October 2006 and July 2007, yielding an exposure of 121.3 kg d in Ge, have been analyzed and the results were recently submitted (3). A blind analysis resulted in zero observed events, the deduced upper limit on WIMP-nucleon spin-independent cross section is 6.6×10^{-44}cm^{2} (4.6×10^{-44}cm^{2}

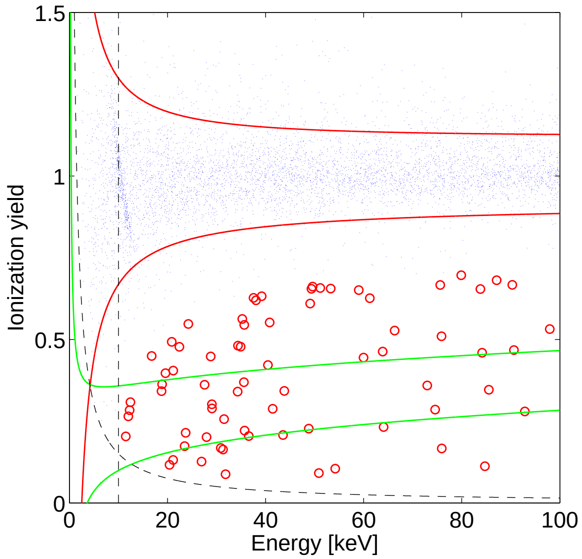

Figure 2.2: Low background data for one ZIP in the ionization yield - energy plane. Electromagnetic background events lie in the (red/upper) electron recoil band, whereas signal events are expected in the (green/lower) nuclear recoil band. The signal region is populated with low yield events (red circles), which are rejected by the surface event timing cut.

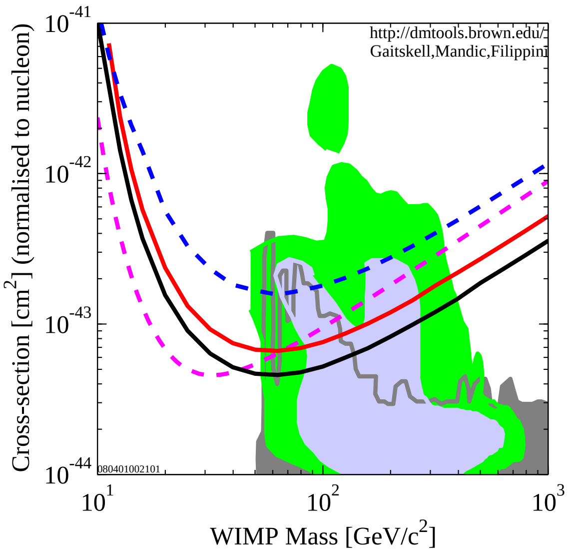

Figure 2.3: Upper limits (90% C.L.) on the spin-independent WIMP-nucleon cross section versus WIMP mass. The upper (blue/dash-dot) curve is a result of a re-analysis of the previous CDMS-II data. The thick (intermediate/red) curve represents the limit derived from the current CDMS-II run. The thick (lower/black) is the combined CDMS-II limit. For comparison the exclusion limit obtained by the XENON10 experiment (orange/dashed) is shown. The filled regions indicate parameter ranges expected from different SUSY models.

when combined with previous CDMS Soudan data) for a WIMP mass of 60 GeV/cm^2 (3). This limit improves upon the sensitivity of XENON10 for WIMP masses above 42 GeV/cm^2, providing the current best sensitivity for dark matter WIMPs above this mass (see also Figs. 2.2 and 2.3). Our group was strongly involved in the analysis of this run (development and tests of analysis cuts, MC simulations of calibration sources and comparison with data, as well as gamma and neutron background studies), and in the operation of the experiment at the Soudan Lab. At the time of this writing, we have accumulated more than an additional ~330 live days, the analysis of this data is ongoing. The expected sensitivity is 2.1×10^{-44}cm^2 for spin-independent WIMP-nucleon cross section at 60 GeV/c^2 WIMP mass by the end of 2008.

The main resposibility of our group are background studies, with focus in understanding the origin and minimizing the sources of background in the ZIP detectors. We performed Monte Carlo simulations of the gamma, beta and internal neutron background using the GEANT4 toolkit, considering contaminations from the $^{238}_{92}$U and $^{232}_{90}$Th chains and decays of $^{60}_{27}$Co and $^{40}_{19}$K in the various materials. The Monte Carlo results were normalized with previously measured activities of these materials. In the case of the gamma background, the predictions could be directly compared to the five tower data, showing an excellent agreement and leaving no unidentifed spectral lines which would indicate an unknown contamination.

The electromagnetic background can be distinguished from a WIMP signal based on the ionization yield parameter, yielding the two well separated bands shown in Fig. 2.2. However, events interacting in the first few microns of the crystal have incomplete charge collection and thus a suppresed ionization yield. Such events can potentially leak into the signal region (given by the lower band) mimicking a WIMP nuclear recoil. These so called low-yield events are identifed as the population below the electron recoil band. Our studies give an average low-yield event rate of 3×10^{-3} counts/(day kg keV) for the current run, with an ambient gamma induced component in the range of 20%. The remaining 80% comes from ^{210}Pb decays on the surface of the detectors. To discriminate between low-yield and nuclear recoil events the timing properties of the phonon signals are used.

Neutrons with MeV energies cause nuclear recoil events identical to the expected signal, however they multiply scatter providing a method to distinguish them from WIMPs. We calculated the neutron spectra and fluxes from $(\alpha, n)-$ and spontaneous fission (SF) reactions for the inner CDMS components (Cu cryostat and ZIP housings) and for the PE and Pb shields. After normalization, the spectra were used in Monte Carlo simulations as neutron-emission probability functions to estimate the induced rates in the ZIP detectors. We expect to detect a total of $\sim 3.1 \cdot 10^{-2}$ ($\sim 1.5 \cdot 10^{-2}$) single neutron recoils in Ge (Si) from internal neutrons for the currently analyzed CDMS exposure (121.3 kg d). The inferred mean single to multiple event ratio is ~1.64.

2.2 Limits on Kaluza-Klein dark matter

In theories with flat universal extra dimensions (UED) (4), two well studied dark matter candidate are $\gamma_{(1)}$, the Kaluza-Klein (KK) photon and Z_1, the KK-Z boson. Their thermal relic density has been calculated (5; 6), including all the relevant coannihilation processes. It is compatible with WMAP results for a wide range of particle masses, and depends for instance on the masses of the first level KK-quarks (5; 6). We have investigated the direct detection of KK dark matter candidates in five and six dimensional UED models. We have compared obtained limits with theoretical predictions for the cross sections and WIMP-nucleon couplings, including both spin-independent and spin-dependent interactions. We have also compute limits on two parameters of the theory, the Higgs mass and the degeneracy parameter Δ_{q_1} defined by

$$\Delta_{q_1} \equiv \frac{m_{q^{(1)}} - m_{L^{(1)}}}{m_{L^{(1)}}} \quad ,$$

which imposes a relation between the assumed to be totally degenerate level one quark masses $m_{q^{(1)}}$ and the mass of the lightest Kaluza-Klein mode $m_{L^{(1)}}$. We were particularly interested in the region of small mass splittings Δ_{q_1}, which is problematic for collider searches, but promising for direct detection.

In Fig. 2.4 we present a combination of results for the case of (a) γ_1 and (b) Z_1 lightest KK-mode in the five dimensional UED. The two most relevant parameters are the mass (m_{γ_1} or m_{Z_1}), and the mass splitting Δ_{q_1}. For simplicity, we assume that the $SU(2)_W$-doublet KK quarks and the $SU(2)_W$-singlet KK quarks are degenerate, so that there is a single mass splitting parameter. Experiments such as CDMS-II and XENON10 can already contrain part of the parameter space (especially for small mass splitting1), while future, 1 ton scale experiments could contrain a significant part of the cosmologically relevant parameter space. A detailed publication with these and further results is in preparation (8).

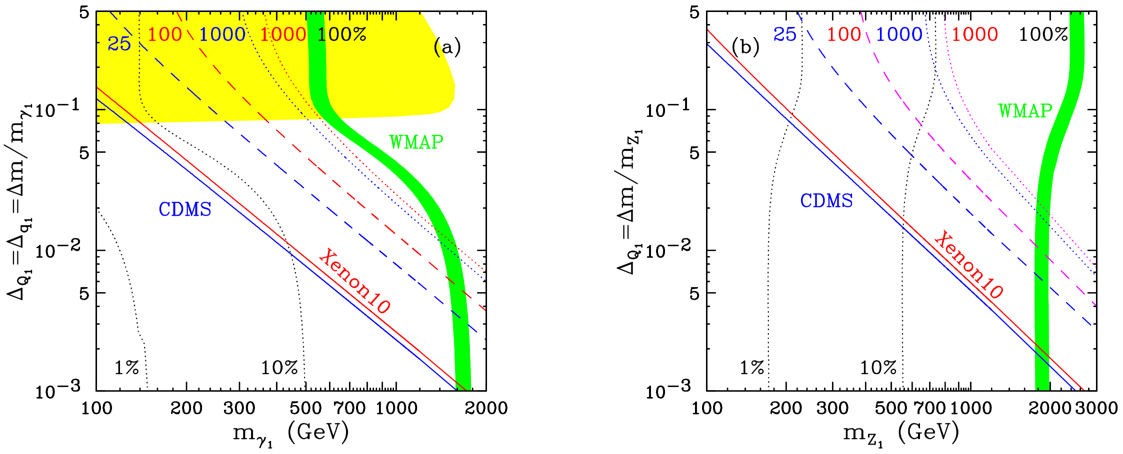

Figure 2.4: Combined plot of the direct detection limits on the spin-independent cross section, the limit from the relic abundance and the LHC reach for (a) γ_1 and (b) Z_1, in the parameter plane of the lightest KK-mode mass and the mass splitting Δ_{q_1}. The SM Higgs mass is m_h=120 GeV. The green band shows the WMAP range for the relic density, 0.1037$<\Omega_{CDM}h^2<$ 0.1161, accounting for 100% of the dark matter. The two black dotted lines show 10% and 1%, respectively. The blue (red) solid line labeled CDMS (XENON10) show the CDMS (XENON10) limit and the dashed and dotted lines represent projected limits for the larger detectors. In the case of γ_1, 1 ton scale experiments rule out most of parameter space while there is little parameter space left in the case of Z_1. The yellow region in the case of γ_1 shows the parameter space that could be covered by the collider search in $4\ell + \not{E}_T$ channel at the LHC with a luminosity of 100 fb^{-1} [7].

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