Underground Searches for Cold Relics of the Early Universe

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We have strong evidence on all cosmic scales, from galaxies to the largest structures ever observed, that there is more matter in the universe than we can see. Galaxies and clusters would fly apart unless they would be held together by material which we call dark, because it does not shine in photons. Although the amount of dark matter and its distribution are fairly well established, we are clueless regarding its composition. Leading candidates are Weakly Interacting Massive Particles (WIMPs), which are 'cold' thermal relics of the Big Bang, ie moving non-relativistically at the time of structure formation. These particles can be detected via their interaction with nuclei in deep-underground, low-background detectors. Experiments dedicated to observe WIMP interactions for the first time reach sensitivities allowing to probe the parameter space predicted by supersymmetric theories of particle physics. Current results of high sensitivity direct detection experiments are discussed and the most promising projects of the future are presented. If a stable new particle exists at the weak scale, it seems likely to expect a discovery within this decade.

1. Introduction

More than seventy years after Zwicky's first accounts of dark matter in galaxy clusters [1], and thirty five years after Rubin's measurements of rotational velocities of spirals [2], the case for non-baryonic dark matter remains convincing. Recent precision observations of the cosmic microwave background [3] and of large scale structures [4] confirm the picture in which more than 90% of the matter in the universe is revealed only by its gravitational interaction. The nature of this matter is not known. A class of generic candidates are weakly interacting massive particles (WIMPs) which could have been thermally produced in the very early universe. It is well known that if the mass and cross section of these particles is determined by the weak scale, the freeze-out relic density is around the observed value, $\Omega \sim 0.1$.

The prototype WIMP candidate is the neutralino, or the lightest supersymmetric particle, which is stable in supersymmetric models where R-parity is conserved. Another recently discussed candidate is the lightest Kaluza-Klein excitation (LKP) in theories with universal extra dimensions. If a new discrete symmetry, called KK-parity is conserved, and if the KK particle masses are related to the weak scale, the LKP is stable and makes an excellent dark matter candidate. A vast experimental effort to detect WIMPs is underway. For excellent recent reviews we refer to [5], [6] and [7]. The good news is that cryogenic experiments are now for the first time probing the parameter space predicted by SUSY theories for neutralinos. On the more pessimistic side, predicted WIMP quark cross sections span several orders of magnitude, and ton or multi-ton scale detectors may be required for a detection. However, such experiments are now in the stage of development, with prototypes being tested and installed in underground labs. The challenge is immense, but the rewards would be outstanding: revealing the major constituents of matter in the universe and their doubtless profound implications for fundamental physics at the weak scale.

2. Direct Detection of WIMPs

WIMPs can be detected directly, via their scattering off nuclei in terrestrial targets [8], or indirectly, via their annihilation products in the Sun, Earth, galactic halo and galactic center with neutrino telescopes and space-based detectors. Here we will briefly discuss direct detection only.

The differential rate for WIMP elastic scattering off nuclei is given by [9]

$$\frac{dR}{dE_R} = N_T \frac{\rho_0}{m_W} \int_{v_{\min}}^{v_{\max}} d\vec{v}\, f(\vec{v})\, v\, \frac{d\sigma}{dE_R}\,, \qquad (1)$$

where N_T represents the number of the target nuclei, m_W is the WIMP mass and ρ_0 the local WIMP density in the galactic halo, $\vec{v}$ and $f(\vec{v})$ are the WIMP velocity and velocity distribution function in the Earth frame and $d\sigma/dE_R$ is the WIMP-nucleus differential cross section.

The nuclear recoil energy is given by $E_R = m_{\rm r}^2 v^2 (1 - \cos\theta)/m_N$, where θ is the scattering angle in the WIMP-nucleus center-of-mass frame, m_N is the nuclear mass and $m_{\rm r}$ is the WIMP-nucleus reduced mass. The velocity $v_{\min}$ is defined as $v_{\min} = (m_N E_{th}/2m_{\rm r}^2)^{\frac{1}{2}}$, where E_{th} is the energy threshold of the detector, and $v_{\max}$ is the escape WIMP velocity in the Earth frame.

The simplest galactic model assumes a Maxwell-Boltzmann distribution for the WIMP velocity in the galactic rest frame, with a velocity dispersion of $v_{rms} \approx 270$ km s^{-1} and an escape velocity of $v_{esc} \approx 650$ km s^{-1}.

The differential WIMP-nucleus cross section can have two separate components: an effective scalar coupling between the WIMP and the nucleus (proportional to A^2, where A is the target atomic mass) and

an effective coupling between the spin of the WIMP and the total spin of the nucleus. In general the coherent part dominates the interaction (depending however on the content of the neutralino) and the cross section can be factorized as $\frac{d\sigma}{dE_R} \propto \sigma_0 F^2(E_R)$, where σ_0 is the point-like scalar WIMP-nucleus cross section and $F(E_R)$ denotes the nuclear form factor, expressed as a function of the recoil energy.

The left side of equation 1 is the measured spectrum in a detector, while the right side represents the theoretical prediction. It includes WIMP properties which are completely unknown, such as the WIMP mass m_W and elastic cross section σ_0, quantities accessible from astrophysics, such as the density of WIMPs in the halo, ρ_0, the WIMP velocity distribution and the escape velocity (which are however prone to large uncertainties) and detector specific parameters: mass of target nucleus, energy threshold and nuclear form factor.

The nuclear form factor becomes significant at large WIMP and nucleus masses, and leads to a suppression of the differential scattering rate. Figure 1 shows differential spectra for Si, Ar, Ge and Xe, calculated for a WIMP mass of 100 Gev, a WIMP-nucleon cross section of $\sigma = 10^{-43}$ cm^2 and using the standard halo parameters mentioned above.
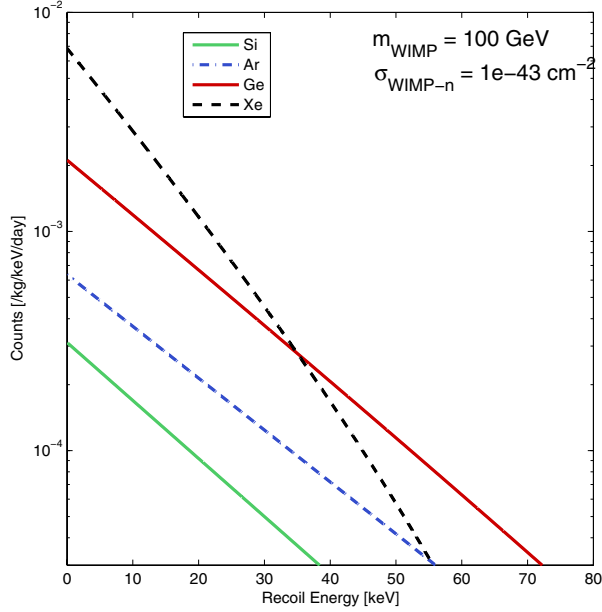

Figure 1: Differential WIMP recoil spectrum for a WIMP mass of 100 GeV and a WIMP-nucleon cross section $\sigma = 10^{-43}$ cm^2. The spectrum was calculated for illustrative nuclei such as Si (light solid), Ar (light dot-dashed), Ge (dark solid), Xe (dark dashed).

A WIMP with a typical mass between a few GeV and 1 TeV will deposit a recoil energy below 50 keV in a terrestrial detector. As for the predicted event rates for neutralinos, scans of the MSSM parameter space

under additional assumptions (GUT, mSUGRA, etc) and accounting for accelerator and cosmological constraints, yield about 10^{-6} to 10 events per kilogram detector material and day [10].

Evidently, in order to observe a WIMP spectrum, low energy threshold, low background and high mass detectors are essential. In such a detector, the recoil energy of the scattered nucleus is transformed into a measurable signal, such as charge, light or phonons, and at least one of the above quantities is detected. Observing two signals simultaneously yields a powerful discrimination against background events, which are mostly interactions with electrons, as opposed to WIMPs and neutrons scattering off nuclei (see Section 3 for a more detailed discussion). Even for experiments with good event by event discrimination, an absolute low background is still important. It can be achieved in both passive and active ways. Passive methods range from high material selection of detector components to various specific shieldings against the natural radioactivity of the environment and against cosmic rays and secondary particles produced in their interactions. Active background reduction implies an active shield, commonly a plastic or liquid scintillator surrounding the detector. An additional advantage is provided by a highly granular detector (or good timing and position resolution), since multiple scatters within the detector volume allow both background reduction and a direct measurement of the neutron background for experiments with an event-by-event discrimination against electron recoils.

In order to convincingly detect a WIMP signal, a specific signature from a particle populating our galactic halo is important. The Earth's motion through the galaxy induces both a seasonal variation of the total event rate [11, 12] and a forward-backward asymmetry in a directional signal [13, 14].

The annual modulation of the WIMP signal arises because of the Earth's motion in the galactic frame, which is a superposition of the Earth's rotation around the Sun and the Sun's rotation around the galactic center:

$$v_E = v_\odot + v_{\rm orb}\,\cos\gamma\,\cos\omega(t - t_0), \qquad (2)$$

where $v_\odot = v_0 + 12$ km s^{-1} ($v_0 \approx 220$ km s^{-1}), $v_{\rm orb} \approx 30$ km s^{-1} denotes the Earth's orbital speed around the Sun, the angle $\gamma \approx 60^0$ is the inclination of the Earth's orbital plane with respect to the galactic plane and $\omega = 2\pi/1{\rm yr}$, $t_0 =$ June 2$^{\rm nd}$.

The expected time dependence of the count rate can be approximated by a cosine function with a period of T = 1 year and a phase of $t_0 =$ June 2$^{\rm nd}$:

$$S(t) = S_0 + S_m cos\omega(t - t_0), \qquad (3)$$

where S_0, S_m are the constant and the modulated amplitude of the signal, respectively. In reality, an

additional contribution to S(t) from the background must be considered. The background should be constant in time or at least not show the same time dependency as the predicted WIMP signal.

The expected seasonal modulation effect is very small (of the order of $v_{orb}/v_0 \simeq 0.07$), requiring large masses and long counting times as well as an excellent long-term stability of the experiment.

A much stronger signature would be given by the ability to detect the axis and direction of the recoil nucleus. In [13] it has been shown, that the WIMP interaction rate as a function of recoil energy and angle θ between the WIMP velocity and recoil direction (in the galactic frame) is:

$$\frac{d^2R}{dE_R dcos\theta} \propto \exp\left[-\frac{(v_\odot cos\theta - v_{min})^2}{v_0^2}\right], \quad (4)$$

where $v_{min}^2 = (m_N + m_W)^2 E_R/2m_N m_W^2$ and $v_0^2 = 3v_\odot^2/2$.

The forward-backward asymmetry thus yields a large effect of the order of $\mathcal{O}(v_\odot/v_0) \approx 1$ and fewer events are needed to discover a WIMP signal than in the case of the seasonal modulation [14]. The challenge is to build massive detectors capable of detecting the direction of the incoming WIMP. At present, only one such detector exists (DRIFT [15]) with a total active mass of $\sim$170 g of CS_2, with larger modules being under consideration.

3. Experiments

First limits on WIMP-nucleon cross sections were derived about twenty years ago, from at that time already existing germanium double beta decay experiments [16]. With low intrinsic backgrounds and already operating in underground laboratories, these detectors were essential in ruling out first WIMP candidates such as a heavy Dirac neutrino [17]. Present Ge ionization experiments dedicated to dark matter searches such as HDMS [18] are limited in their sensitivity by irreducible electromagnetic backgrounds close to the crystals or from cosmogenic activations of the crystal themselves. Next generation projects based on high-purity germanium (HPGe) ionization detectors, such as the proposed GENIUS [19], GERDA [20], and Majorana [21] experiments, aim at an absolute background reduction by more than three orders in magnitude, compensating for their inability to differentiate between electron- and nuclear recoils on an event-by-event basis. Note that the primary scientific goal of these projects is to look for the neutrinoless double beta decay, at a Q-value around 2039 keV in ^{76}Ge. Solid scintillators operated at room temperatures had soon caught up with HPGe experiments, despite their higher radioactive backgrounds. Being

intrinsically fast, these experiments can discern on a statistical basis between electron and nuclear recoils, by using the timing parameters of the pulse shape of a signal. Typical examples are NaI experiments such as DAMA [22] and NAIAD [23], with DAMA reporting first evidence for a positive WIMP signal in 1997 [24]. The DAMA results have not been confirmed by three different mK cryogenic experiments (CDMS [25, 26], CRESST [27] and EDELWEISS [28, 29]) and one liquid xenon experiment (ZEPLIN [30]), independent of the halo model assumed [34] or whether the WIMP-nucleon interaction is taken as purely spin-dependent [32, 33]. The DAMA collaboration has installed a new, 250 kg NaI experiment (LIBRA) in the Gran Sasso Laboratory, and began taking data in March 2003. With lower backgrounds and increased statistics, LIBRA should soon be able to confirm the annual modulation signal. The Zaragosa group plans to operate a 107 kg NaI array (ANAIS) at the Canfranc Underground Laboratory (2450 mwe) in Spain [35], and deliver an independent check of the DAMA signal in NaI. Cryogenic experiments operated at sub-Kelvin temperatures are now leading the field with sensitivities of one order of magnitude above the best solid scintillator experiments. Specifically, the CDMS experiment can probe WIMP-nucleon cross sections as low as 10^{-43}cm^2 [26]. This class of experiments will be covered in more detail in Section 3.1. Liquid noble element detectors are rapidly evolving, and seem a very promising avenue towards the goal of constructing ton-scale or even multi-ton WIMP detectors. These approaches will be discussed in Section 3.2. Many other interesting WIMP search techniques have been deployed, and it is not the scope of this paper to deliver a full overwiev. For a significantly more detailed accounting of existing and future detection techniques, as well as critical discussions of backgrounds and of the reported positive signal, we refer to two recent reviews [5, 6].

3.1. Cryogenic Detectors at mK Temperatures

Cryogenic calorimeters are meeting crucial characteristics of a successful WIMP detector: low energy threshold (<10 keV), excellent energy resolution (<1% at 10 keV) and the ability to differentiate nuclear from electron recoils on an event-by-event basis. Their development was driven by the exciting possibility of doing a calorimetric energy measurement down to very low energies with unsurpassed energy resolution. Because of the T^3 dependence of the heat capacity of a dielectric crystal, at low temperatures a small energy deposition can significantly change the temperature of the absorber. The change in temperature can be measured either after the phonons (or lattice vibration quanta) reach equilibrium, or ther-

malize, or when they are still out of equilibrium, or athermal, the latter providing additional information about the location of an event. The astounding energy resolution comes from the fact that a much lower energy ($<1\,$meV) is required to produce an elementary phonon excitation compared to semiconductor detectors ($\sim1\,$eV). If a second signal, such as charge or scintillation light is detected, identification of background events induced by electron recoils is possible. It is based on the measured difference in the ratio of charge or light to phonons for electron and nuclear recoils. If a class of events (such as, for example, interactions within tens of micrometers of the detector's surface) results in incomplete charge or light collection, then such events can leak into the parameter region predicted for nuclear recoils. As will be discussed later, no such events have been observed yet in phonon-light detectors. On the other hand, the timing properties of the fast phonon signal in certain phonon-charge detectors allow a discrimination between surface events and interactions in the bulk.

3.1.1. CDMS

The Cold Dark Matter Search experiment operates low-temperature Ge and Si detectors at the Soudan Underground Laboratory in Minnesota (at a depth of 2080 m.w.e.). The high-purity Ge and Si crystals are 1 cm thick and 7.6 cm in diameter, and have a mass of 250 g and 100 g, respectively. They are operated at a base temperature around 50 mK. Superconducting transition edge sensors photolitographically patterned onto one of the crystal surfaces detect the athermal phonons from particle interactions. The phonon sensors are divided into 4 different channels, allowing to reconstruct the x-y position of an event with a resolution of $\sim1\,$mm. If an event occurs close to the detector's surface, the phonon signal is faster than for events far from the surface, because of phonon interactions in the thin metallic films. The risetime of the phonon pulses, as well as the time difference between the charge and phonon signals allow to reject surface events caused by electron recoils. Figure 2 shows phonon start times versus ionization yield (charge energy divided by the total recoil energy) for electron recoil events (collected with a ^{133}Ba source) and nuclear recoil events (collected with a ^{252}Cf source). Events below a yield around 0.75 typically occur within 0-$30\,\mu$m of the surface, and can be effectively discriminated (a typical rise time cut is shown by the horizontal grey line in the figure) while preserving a large part of the nuclear recoil signal.

Charge electrodes are used for the ionization measurement. They are divided into an inner disk, covering 85% of the surface, and an outer guard ring, which is used to reject events near the edges of the crystal, where background interactions are more likely to occur. Figure 3 shows a picture of CDMS detectors in their Cu holders.
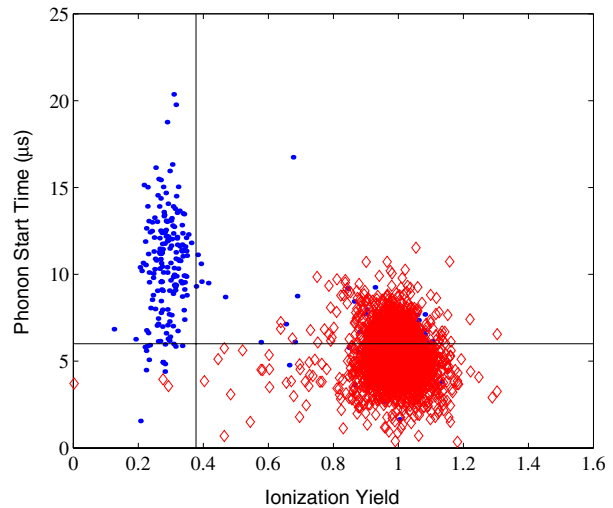

Figure 2: Phonon start times versus ionization yield for ^{133}Ba gamma calibration events (diamonds) and ^{252}Cf neutron calibration events (dots). The grey lines indicate timing and ionization-yield cuts, resulting in a high-rate of nuclear recoil efficiency and a low rate of misidentified surface events.
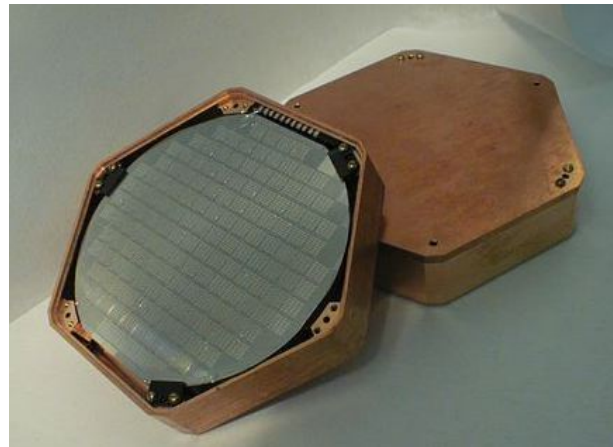

Figure 3: CDMS detectors (250 g Ge or 100 g Si, 1 cm thick and 7.5 cm diameter) in their Cu holders.

The discrimination against the electron recoil background is based on the fact that nuclear recoils (caused by WIMPs or neutrons) produce fewer charge pairs than electron recoils of the same energy. The ionization yield, defined as the ratio of ionization to recoil energy, is about 0.3 in Ge, and 0.25 in Si for recoil energies above 20 keV. Electron recoils with complete charge collection show an ionization yield of ≈1. For recoil energies above 10 keV, bulk electron recoils are rejected with $>99.9\%$ efficiency, and surface events are rejected with $>95\%$ efficiency. The two different materials are used to distinguish between WIMP and neutron interactions by comparing the rate and the spectrum shape of nuclear recoil events. While the interaction rate of neutrons is comparable in Ge and

Si, the WIMP rate is much higher in Ge for spin-independent couplings.

A stack of six Ge or Si detectors together with the corresponding cold electronics is named a 'tower'. Five towers (30 detectors) are currently installed in the 'cold volume' at Soudan, shielded by about 3 mm of Cu, 22.5 cm of Pb, 50 cm of polyethylene and by a 5 cm thick plastic scintillator detector which identifies interactions caused by cosmic rays penetrating the Soudan rock. Results from the first tower of 4 Ge and 2 Si detectors [26], which took data at Soudan from October 2003 to January 2004, showed no nuclear recoil candidate in 53 raw live days (see Figure 4).
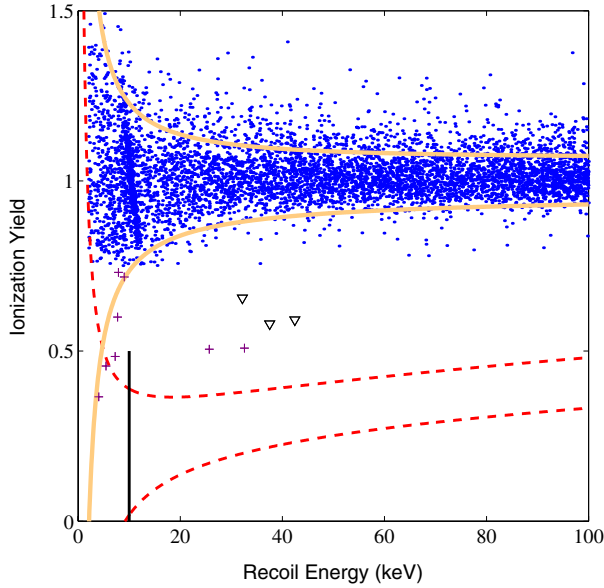

Figure 4: Ionization yield versus recoils energy for 3 Ge detectors of Tower 1 for a total lifetime of 53 kg days. Events above an ionization yield of 0.75 are shown as points (note the 10.4 keV Ga X-ray line), events below a yield of 0.75 are shown as geometrical shapes. The expected signal region for WIMP recoils lies between the two dashed lines around a yield of 0.3. The dark vertical line denotes the analysis threshold of 10 keV recoil energy.

After cuts, the net exposure was 22 kg days for Ge and 5 kg days for Si. The resulting upper limit on WIMP-nucleon cross sections for spin-independent couplings and a standard halo is 4×10^{-43}cm^2 at the 90% C.L. at a WIMP mass of 60 GeV (see Figure 5), which is four times below the best previous limit reported by EDELWEISS [28].

The limits on spin-dependent WIMP interactions are competitive with other experiments, in spite of the low abundance of ^{73}Ge (7.8%) in natural germanium. In particular, in the case of a pure neutron coupling, CDMS yields the most stringent limit obtained so far, thus strongly constraining interpretations of the DAMA signal region [33, 36] (Figure 6).
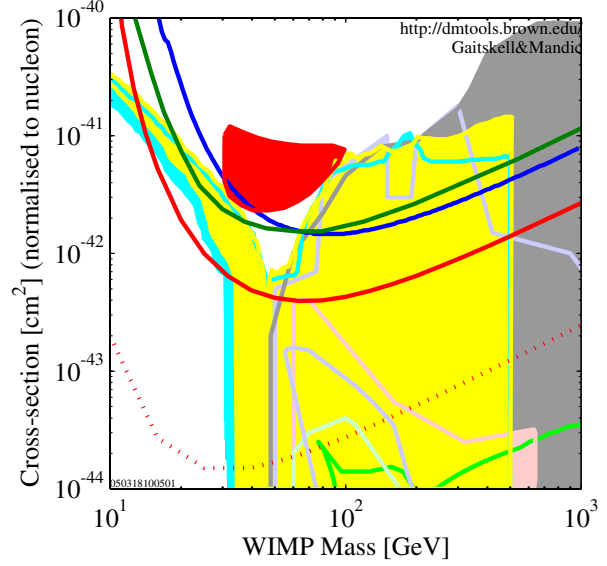

Figure 5: Experimental results and theoretical predictions for spin-independent WIMP nucleon cross sections versus WIMP mass. The data (from high to low cross sections) show the DAMA allowed region (red) [24], the latest EDELWEISS result (blue) [29], the ZEPLIN I preliminary results (green) [30] and the CDMS results from Tower 1 at Soudan (red) [26]. Also shown is the expectation for 5 CDMS towers at Soudan (red dashed). The SUSY theory regions are shown as filled regions or contour lines, and are taken from [31].
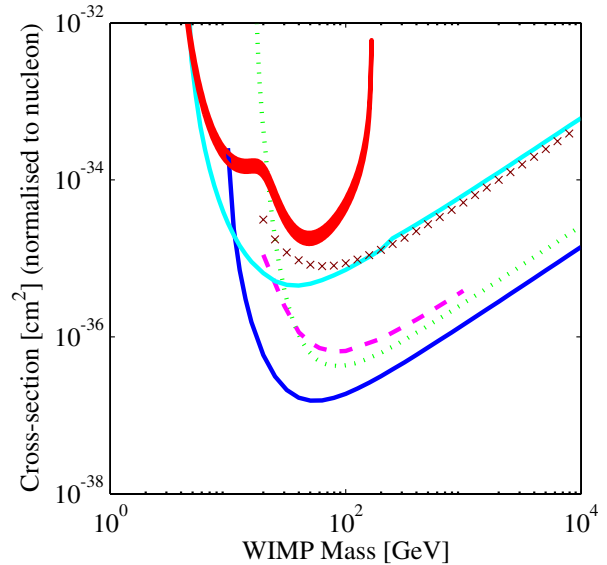

Figure 6: Experimental results for spin-dependent WIMP couplings (90% C.L. contours), for the case of a pure neutron coupling. The curves (from high to low cross sections) show the DAMA annual modulation signal (filled red region), the CDMS Soudan Si data (red crosses), the CDMS Stanford Si data (cyan), EDELWEISS (magenta dashed), DAMA/Xe (green dotted) and the CDMS Soudan Ge data (solid blue). For details and references see [38].

For details on the CDMS analysis for spin-dependent WIMP couplings we refer to Jeff Filippini's contribution to these proceedings [38].

Two towers (6 Ge and 6 Si detectors) were operated at Soudan from March to August 2004. The data is being currently analyzed in a similar fashion to the first Soudan run, in which all cuts are determined in a blind manner from calibration data, without access to the signal region. Calibration runs were interspersed with science runs, and taken with a ^{252}Cf (neutron and gamma) and a ^{133}Ba (gamma) source. The high-statistics Ba data also allows for a calibration to surface events, providing a population of so called 'ejectrons', or low energy electrons which are ejected from an adjacent detector of from material close to a detector's surface. For an overview of the currently running experiment at Soudan and expectations from the 5 tower run in 2005, we refer to Walter Ogburn's contribution to these proceedings [39].

3.1.2. EDELWEISS

The EDELWEISS experiment operates germanium bolometers at 17 mK in the Laboratoire Souterrain de Modane, at about 4800 m.w.e. The detectors are further shielded by 30 cm of paraffin, 15 cm of Pb and 10 cm of Cu. As in the case of CDMS, they simultaneously detect the phonon and the ionization signals, allowing a discrimination against bulk electron recoils of better than 99.9% above 15 keV recoil energy. The charge signal is measured by Al electrodes sputtered on each side of the crystals, the phonon signal by a neutron transmutation doped (NTD) heat sensor glued onto one of the charge collection electrodes. The NTD sensors read out the thermal phonon signal on a time scale of about 100 ms. Figure 7 shows a picture of a 320 g germanium bolometer.

Figure 7: Photograph of a 320 g EDELWEISS germanium bolometer.

Between 2000-2003, EDELWEISS performed four physics runs with five 320 g Ge crystals, accumulating a total exposure of 62 kg days [40]. Above an analysis threshold of 20 keV, a total of 23 events compatible with nuclear recoils have been observed. Figure 8 shows the ionization yield versus recoil energy for one EDELWEISS detector for an exposure of 9.16 kg days.

The derived upper limit on spin-independent WIMP-nucleon couplings under the hypothesis that all above events are caused by WIMP interactions, and for a standard isothermal halo, is shown in Figure 5. The allowed region in the (a_n, a_p) plane for spin-dependent WIMP couplings is shown in Figure 9, for a WIMP mass of 50 GeV ($a_{p,n}$ are the effective WIMP couplings to proton and neutrons).
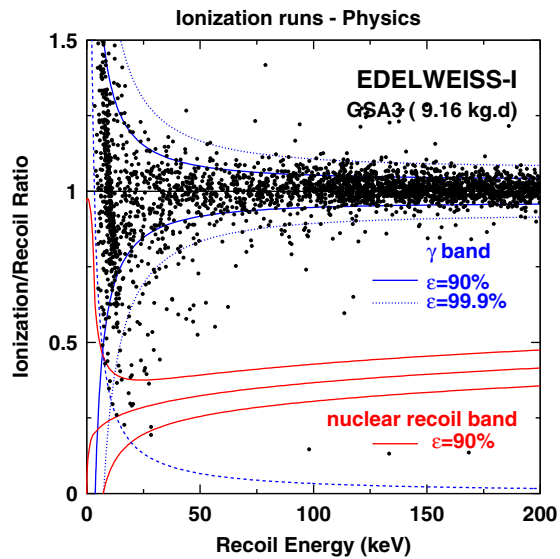

Figure 8: Ionization yield versus recoil energy for one EDELWEISS 320 g Ge detector with an exposure of 9.16 kg days. Also shown are the electron recoil (blue) and neutron recoil (red) bands. Figure taken from [29].

The EDELWEISS experiment has ceased running in March 2004, in order to allow the upgrade to a second phase, with an aimed sensitivity of 10^{-44}cm^2. The new 50 liter low-radioactivity cryostat will be able to house up to 120 detectors. Because of the inability of slow thermal detectors to distinguish between low-yield surface events and nuclear recoils and the inherent radioactivity of NTD sensors, the collaboration has been developing a new design based on NbSi thin-film sensors. These films, besides providing a lower mass and radioactivity per sensor, show a strong difference in the pulse shape, depending on the interaction depth of an event [42]. The EDELWEISS collaboration plans to operate twenty-one 320 g Ge detectors equipped with NTD sensors, and seven 400 g Ge detectors with NbSi thin-films in the new cryostat starting in 2005.
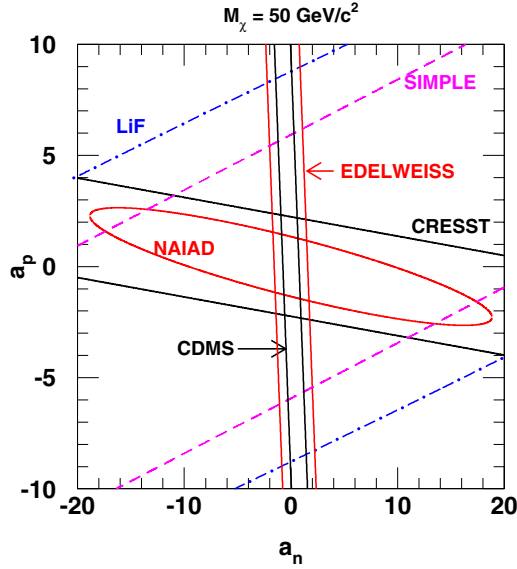
Figure 9: Allowed regions in the (a_n, a_p) plane for a WIMP mass of 50 GeV. $a_{p,n}$ are the effective WIMP couplings to proton and neutrons (see [41] for details). The allowed regions are those within the parallel straight lines or ellipses.

3.1.3. CRESST

The CRESST collaboration has developed cryogenic detectors based on $CaWO_4$ crystals, which show a higher light yield at low temperatures compared to other scintillating materials. The detectors are also equipped with a separate, cryogenic light detector made of a $30{\times}30{\times}0.4\,mm^3$ silicon wafer, which is mounted close to a flat surface of the $CaWO_4$ crystal. The temperature rise in both $CaWO_4$ and light detector is measured with tungsten superconducting phase transition thermometers, kept around 10 mK, in the middle of their transition between the superconducting and normal conducting state. A schematic picture and a photograph of a CRESST detector is shown in Figure 10.
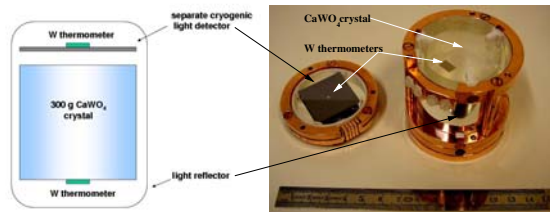

Figure 10: Schematic picture and photograph of a CRESST $CaWO_4$ light and phonon detector. Figure taken from [27].

A nuclear recoil in the 300 g $CaWO_4$ detector has a different scintillation light yield than an electron recoil of the same energy, allowing to discriminate between the two type of events when both the phonon and the light signals are observed. The advantage of $CaWO_4$ detectors is their low energy threshold in the phonon signal, and the fact that no light yield degradation for surface events has been detected so far. However, about 1% or less of the energy deposited in the $CaWO_4$ is seen as scintillation light [27]. Only a few tens of photons are emitted per keV electron recoil, a number which is further diminished for nuclear recoils, because of the involved quenching factor. The quenching factor of oxygen nuclear recoils for scintillation light is around 13.5% relative to electron recoils [27], leading to a rather high effective recoil energy threshold for the detection of the light signal. While neutrons will scatter predominantly on oxygen nuclei, it is expected that WIMPs will more likely scatter on the heavier calcium and tungsten. The quenching factor of tungsten at room temperatures has been measured to be around 2.5% [27], making it difficult to observe the light signal of WIMP recoils above the thermal noise.

The most recent CRESST results were obtained by operating two 300 g $CaWO_4$ detectors at the Gran Sasso Underground Laboratory (3800 m.w.e) for two months at the beginning of 2004 [27]. The total exposure after cuts was 20.5 kg days. The energy resolution in the phonon channel was 1.0 keV (FWHM) at 46.5 keV, the low-energy gamma line being provided by an external ^{210}Pb contamination. A total of 16 events were observed in the 12 keV - 40 keV recoil energy region, a number which seems consistent with the expected neutron background, since the experiment had no neutron shield at this stage. No phonon-only events (as expected for WIMP recoils on tungsten) were observed between 12 keV - 40 keV in the module with better resolution in the light channel, yielding a limit on coherent WIMP interaction cross sections very similar to the one obtained by EDELWEISS.

CRESST has stopped taking data in March 2004, to upgrade with a neutron shield, an active muon veto, and a 66-channels SQUID read-out system. It will allow to operate 33 $CaWO_4$ detector modules, providing a total of 10 kg of target material. The upgrade will be completed in early 2005 and the expected sensitivity is around $10^{-44}cm^2$.

3.2. Liquid Xenon Detectors

Liquid xenon (LXe) has excellent properties as a dark matter detector. It has a high density ($3\,g/cm^3$) and high atomic number (Z=54, A=131.3), allowing experiments to be compact. The high mass of the xenon nucleus is favorable for WIMP scalar interactions provided that a low energy threshold can be achieved (see Figure 1 for a comparison with other

target nuclei). LXe is an intrinsic scintillator, having high scintillation ($\lambda = 178$ nm) and ionization yields because of its low ionization potential (12.13 eV). There are no long-lived radioactive xenon isotopes, and other impurities (such as ^{85}Kr) can be reduced to a very low level by centrifugation or with a distillation tower and a cold trap. Krypton contamination levels as low as 1 ppb (parts per billion) have already been achieved [44].

Scintillation in liquid xenon is produced by the formation of excimer states, which are bound states of ion-atom systems. If a high electric field (~ 1 kV/cm) is applied, ionization electrons can also be detected, either directly or through the secondary process of proportional scintillation.

The elastic scattering of a WIMP produces a low-energy xenon recoil, which loses its energy through ionization and scintillation. Both signals are quenched when compared to an electron recoil of the same energy, but by different amounts, allowing to use the ratio for distinguishing between electron and nuclear recoils. The quenching factor for both scintillation and ionization depends on the drift field and on the energy of the recoil.

At zero electric field, the relative scintillation efficiency of nuclear recoils in LXe was recently measured to be in the range of 0.13-0.23 for Xe recoil energies of 10 keV-56 keV [45].

There are three efforts to develop liquid xenon detectors operated in the dual-phase (liquid and gas) mode.

3.2.1. ZEPLIN

The Boulby Dark Matter collaboration has been operating a single-phase liquid xenon detector, ZEPLIN I, at the Boulby Mine (~ 3000 m.w.e.) during 2001-2002. The ZEPLIN I detector had a fiducial mass of 3.2 kg of liquid xenon, viewed by 3 PMTs through silica windows. It was inclosed in a 0.93 ton active scintillator veto, which helped in reducing the background from the radioactivity of the PMTs and surroundings. A picture inner detector is shown in Figure 11.

A total exposure of 293 kg days had been accumulated. With a light yield of 1.5 electrons/keV, the energy threshold was at 2 keV electron recoil (corresponding to 10 keV nuclear recoil energy for a quenching factor of 20%). A discrimination between electron and nuclear recoils was applied by using the difference in the mean time of the corresponding pulses. To establish this difference, the detector had been calibrated with gamma sources (above ground and at the mine), and with neutron sources above ground. Using this statistical discrimination, a preliminary limit on spin-independent WIMP cross sections comparable to CRESST and EDELWEISS has been achieved (see Figure 5).

Figure 11: Photograph of the ZEPLIN I inner liquid xenon detector.

The collaboration has developed two concepts for dual-phase detectors, ZEPLIN II and ZEPLIN III. ZEPLIN II will have a 30 kg fiducial target mass, observed by 7 PMTs. ZEPLIN III will operate a lower target mass (6 kg liquid xenon viewed by 31 PMTs) at a higher field (> 5 kV/cm). It is expected that both ZEPLIN II and ZEPLIN III will be deployed at the Boulby Mine in 2005.

3.2.2. XMASS

The Japanese XMASS collaboration develops liquid xenon detectors for solar neutrinos, double beta decay and dark matter searches [46]. Since 2003, they have been operating a 1 kg dual-phase detector at the Kamioka Mine (2700 mwe). The active volume was viewed by two UV-sensitive PMTs through MgF_2 windows, the detector being operated in the low drift field regime (250 V/cm) [47]. At such fields, the proportional light signal is large for electron recoils, but very small or zero for nuclear recoils. Events which yield a signal only in the light channel can thus mimic a potential WIMP candidate. A second prototype with an active volume of 15 kg viewed by 14 PMTs is currently under operation at the Kamioka Underground Laboratory. A 100 kg single-phase detector is also being operated at Kamioka [46]. Thirty liters of liquid xenon are contained in a $(31 \text{ cm})^3$ oxygen free copper vessel, and viewed by 54 low-background, 2 inch PMTs. So far, the background levels are consistent within a factor of two with expectations, although an internal ^{222}Rn source has been detected [46].

3.2.3. XENON

The US XENON collaboration plans to deploy and operate a 10 kg dual-phase detector in the Gran Sasso Underground Laboratory (3500 m.w.e) by 2005-2006. At present, a 3 kg prototype is under operation above ground, at the Columbia Nevis Laboratory [43]. The detector is operated at a drift field of 1 kV/cm, and both primary and proportional light are detected by an array of seven 2 inch PMTs operating in the cold gas above the liquid. The active volume is defined by PTFE walls and Be-Cu wire grids with high optical transmission. The detector is insulated by a vacuum cryostat and cooled down to a stable temperature of (-100 ± 0.05) C with a pulse tube refrigerator (see Figure 12 for a schematic drawing of the prototype and Figure 13 for a picture of the cryostat.).
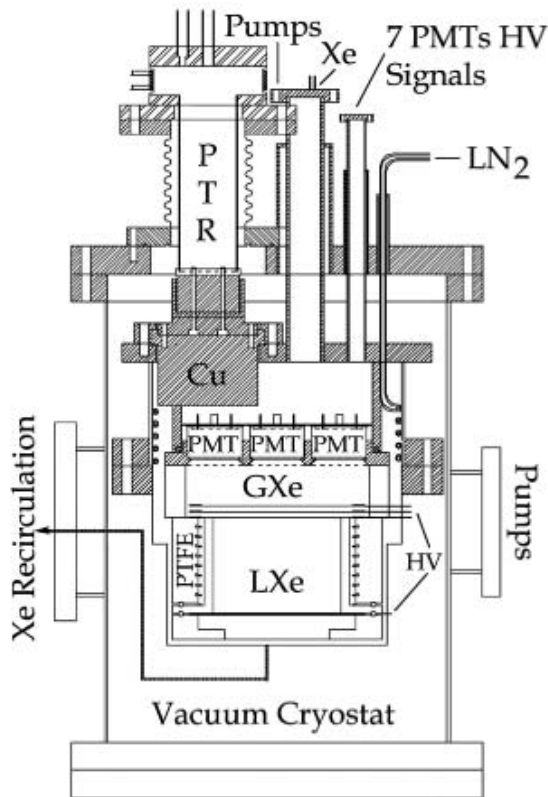

Figure 12: Schematic drawing of the 3 kg XENON dual phase prototype.

The xenon gas is continuously circulated and purified using a high temperature SAES getter [48]. The performance of the chamber was tested with gamma (^{57}Co), alpha (^{210}Pb) and neutron (^{241}AmBe) sources. The depth of an event is reconstructed by looking at the separation in time between the primary and proportional scintillation signal (the electron drift velocity for the applied electric field is known). The x-y position is inferred with a resolution of 1 cm from the center of gravity of the proportional light emit-

ted close to the seven PMTs. The measured ratio of proportional light (S2) to direct light (S1) for alpha recoils is 0.03 if the corresponding ratio for gamma events (electron recoils) is normalized to 1, providing a very clear separation between these type of events.
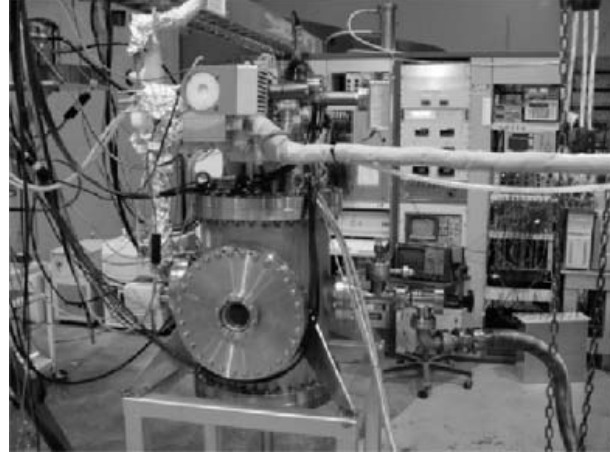

Figure 13: Picture of the 3 kg (active mass) XENON dual phase cryostat.

More interesting is the ratio S2/S1 for nuclear recoil events. It was established using a ^{241}AmBe neutron source, by selecting events which were tagged as neutron recoils in a separate neutron detector placed under a scattering angle of 130 deg. If the S2/S1 ratio for electron recoils (provided by a ^{137}Cs source) is again normalized to 1, then S2/S1 for nuclear recoils was measured to be around 0.1, the leakage of electron recoils into the S2/S1 region for nuclear recoils being $< 1\%$ (for details see [43]). Figure 14 shows a histogram of S2/S1 for events taken with the ^{241}AmBe source, compared to the corresponding distribution of events from the ^{137}Cs gamma source.

These first measurements are very encouraging, and will be further improved by using a CsI photocathode immersed in the liquid. The downwards going primary photons are converted into electrons, which are then drifted into the gas phase, where electroluminiscence occurs and a tertiary signal is observed by the PMTs. First tests of a CsI photocathode in the 3 kg prototype have confirmed the high quantum efficiency (around 12% at 1 kV/cm) which had been previously measured [49].

The first XENON detector with a fiducial mass of 10 kg (XENON10) to be operated in Gran Sasso is currently under construction. Its goal is to achieve a sensitivity of a factor of 20 below the current CDMS results, thus probing WIMP cross sections around 2×10^{-44}cm^2.
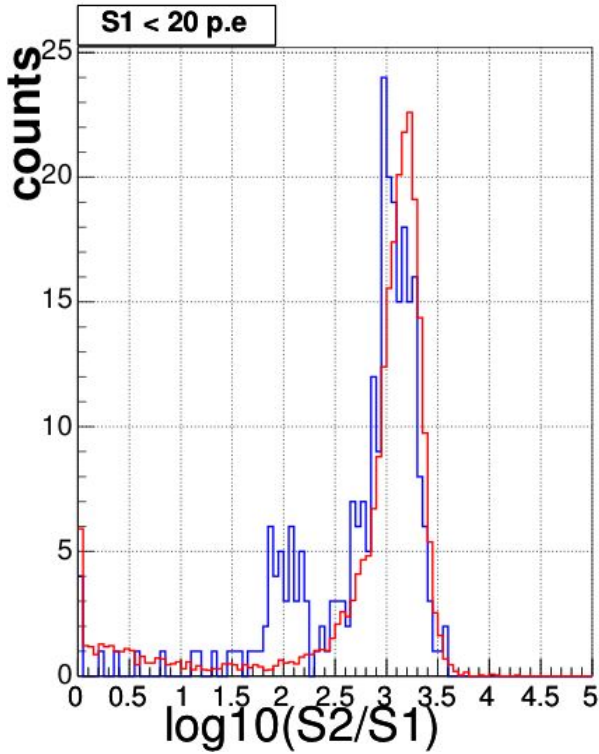
Figure 14: Histogram showing the S2/S1 distribution for AmBe events (blue) versus 662 keV gamma events from ^{137}Cs (red). Two distinct populations are visible in the AmBe data. Figure taken from [43].

3.3. The Future

We live in suspenseful times for the field of direct detection: for the first time, a couple of experiments operating deep underground probe the most optimistic supersymmetric models. The best limits on WIMP-nucleon cross sections come from cryogenic experiments with ultra-low backgrounds and excellent event-by-event discrimination power (CDMS, EDELWEISS, CRESST). Although these experiments had started with target masses around 1 kg, upgrades to several kilograms have already taken place or are foreseen for the near future, ensuring (along with improved backgrounds) an increase in sensitivity by a factor of 10-100. Other techniques, using liquid noble elements such as xenon, may soon catch up and probe similar parameter spaces to low-temperature cryogenic detectors. It is worth emphasizing here that given the importance of the endeavor and the challenge in unequivocally identifying and measuring the properties of a dark matter particle, it is essential that more than one technique will move forward.

If supersymmetry is the answer to open questions in both cosmology and particle physics, then WIMP-nucleon cross sections as low as 10^{-48}cm^2 are likely [50]. Likewise, in theories with universal extra dimensions, it is predicted that the lightest Kaluza Klein particle would have a scattering cross section with nucleons in the range of 10^{-46} - 10^{-48}cm^2 [51]. Thus, to observe a signal of a few events per year, ton or even multi-ton experiments are inevitable. There are several proposals to build larger and improved dark matter detectors (see [5] for an exhaustive list). The selection presented below is likely biased, but based on technologies which seem the most promising to date.

The SuperCDMS project is a three-phase proposal to utilize CDMS-style detectors with target masses growing from 27 kg to 145 kg and up to 1100 kg, with the aim of reaching a final sensitivity of 3×10^{-46}cm^2 by mid 2015. This goal will be realized by developing improved detectors (for a more precise event reconstruction) and analysis techniques, and at the same time by strongly reducing the intrinsic surface contamination of the crystals. A possible site for Super-CDMS is the recently approved SNO-Lab Deep-site facility in Canada (at 6000 m.w.e.), where the neutron background would be reduced by more than two orders of magnitude compared to the Soudan Mine, thus ensuring the mandatory conditions to build a zero-background experiment. For details on the SuperCDMS project we refer to Paul Brink's contribution to these proceedings [52]. In Europe, a similar project to develop a 100 kg-1 ton cryogenic experiment, EURECA (European Underground Rare Event search with Calorimeter Array) [6] is underway. The XENON collaboration is designing a 100 kg scale dual-phase xenon detector (XENON100), towards a modular one tonne experiment. The baseline goal is 99.5% background rejection efficiency above a 16 keV nuclear recoil energy threshold, full 3-D localization of an event and a liquid xenon self shielding surrounding the detector. The aim of XENON100 is to probe the parameter space down to cross sections of 10^{-45}cm^2. The full scale, one tonne experiment (XENON1t), which will operate ten XENON100 modules, will increase this sensitivity by another order of magnitude [43]. ZEPLIN MAX, a R&D project of the Boulby Dark Matter collaboration, is a further proposal to build a ton scale liquid xenon experiment. The design will be based on the experience and results with ZEPLIN II/III at the Boulby Mine [30].

In looking back over the fantastic progress made in the last couple of years, and extrapolating into the future, it seems probable that these, and other proposed projects, will have a fair chance to discover a WIMP signature within the present decade. In conjunction with indirect searches and accelerator production of new particles at the weak scale, they will allow to reveal the detailed properties of WIMPs, such as their mass, spin and couplings to ordinary matter, and shed light on their velocity and spatial distribution in our galactic halo.

Acknowledgments

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