Dark Matter direct detection searches

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The present experimental status of direct searches for Dark Matter is presented. These experiments look for energetic recoiling ions produced by the scattering on terrestrial targets of WIMP particles from our galactic halo. They put the strictest constraints on the spin-independent cross-section for this process. The status and prospects of some currently running experiments are presented.

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Direct searches for Dark Matter in the form of Weakly Interacting Massive Particles (WIMPs) are experiments looking for energetic recoiling ions produced by the scattering of such a particle on laboratory targets. The growing interest for these experiments stems from the continuous flow of cosmological and astrophysical observations that underlines the need for a large fraction of the mass of the Universe to come from a yet undetected form of matter that does not absorb or emit electromagnetic radiation, and has decoupled from ordinary matter and become non-relativistic early enough in the history of the Big Bang to explain the formation of large structures (for more details, see e.g. Refs. [1]). An elegant solution is provided by particles having weak-force interactions such as the neutralino acting as the lightest Supersymmetric (SUSY) particle, as it is often the case in minimal version of this model (MSSM). In this scenario, a conclusive identification could be performed by combining the results of MSSM tests at LHC with those of direct searches and other experiments looking for WIMP annihilation products in cosmic ray (indirect searches). In the event of the discovery of WIMPs at colliders, direct searches would be essential at proving that these are indeed present in the halo of our Galaxy.

The present review describes the principles of direct searches for Dark Matter, and presents the status and prospects of some of the leading currently-running experiments.

1. Direct Searches

Direct searches aim at measuring the rate and the energy spectrum of nuclear recoils induced by collisions with WIMPs. The four factors entering the expression of this rate are: the local WIMP density, their velocity distribution relative to Earth, their scattering cross-section on a nucleon, and a coherence factor that takes into account that the nuclear target is made of A nucleons. The uncertainties associated to these factors can be large and must be kept in mind when comparing experimental results with theoretical predictions. In order to have a consistent comparison between the sensitivity of different experiments, one generally use the conventions laid out by Lewin and Smith [2] concerning the local WIMP density and the choice of a Maxwellian velocity distribution, to which the Sun and Earth velocities are added. More complex halo models have been considered [3], but the conventional values are still relevant for the sake of comparing experiments. The WIMP-nucleon scattering cross-section σ_n is taken from model predictions. However two cases can be distinguished for its scaling to a WIMP-nucleus cross-section σ_A. In the case of spin-dependent interactions, the scaling factor is $J(J+1)$, where J is the nuclear spin. For spin-independent interactions, the factor is A^2, where A is the atomic mass of the target nucleus. A kinematic factor $\sim A^2$ also intervenes in the definition of the cross-section. The additional contribution from nuclear form factors dampens somewhat the A dependence, but in most models the spin-independent amplitude dominates, favouring target nuclei with large A values. Fig. 1 compares the expected number of counts above threshold observed after a one-year exposure of 1 kg of different target materials, for a spin-independent cross-section of 10^{-8}pb and a WIMP mass of 100 GeV$\cdot$c^{-2}, calculated using the prescriptions of Lewin and Smith [2]. Larger A values are generally associated with larger rates, but the experimental threshold in recoil energy also matters. In order to be relevant for a wide range of models, searches results are expressed as excluded or preferred regions in a graph of σ_n versus M_W (Right pannel of Fig. 1). This figure displays the most constraining experimental limits on the spin-independent cross-section, together with the regions

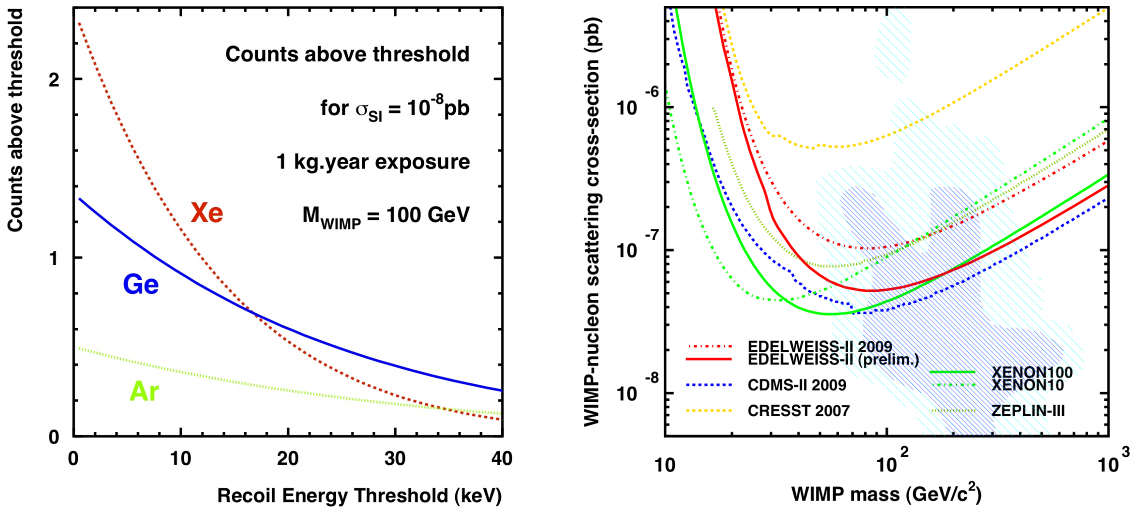

Figure 1: Left pannel: Expected number of counts above threshold as a function of this threshold, in a one-year exposure of 1 kg of different target materials for a spin-independent cross-section of 10^{-8}pb and a WIMP mass of 100 GeV·c^{-2}, calculated using the prescriptions of Ref. [2]. Right: Exclusions limits for the spin-independent WIMP scattering cross-section as a function of the mass of the WIMP from different direct search experiments (see text). The hashed lines corresponds to Constrained MSSM models from Ref. [4] .

favored in some Constrained MSSMs [4]. The cross-sections generally decrease with mass. The accumulation of models around 10^{-8}pb (the so-called "Focus-Point") correspond to experimental rates of approximately 1 event per kg·year (left pannel of Fig. 1), making this an attractive goal for current direct searches experiments. Precise comparisons of experiments and predictions requires a thorough discussions of the model uncertainties. Cross-sections as low as 10^{-11}pb appear for large WIMP masses or in less-constrained models, corresponding to rates close to one event per ton·year, setting the scale for future large experiments.

The main challenge in direct searches is the low expected rates, requiring an extreme suppression of natural radioactivity in the relevant recoil energy range. As a comparison, the natural radioactivity of the human body is ten orders of magnitude above the rate associated to a cross-section of 10^{-8}pb. Thus, the detector and its surroundings must be made of rigorously selected materials, with massive shielding and a protection from cosmic activation that can only be achieved in deep underground locations. What remains after this large suppression often comes from poorly understood tails of distributions and tiny detector imperfections. These are difficult to model, as present-day detectors often probe unchartered levels of low backgrounds in this domain of recoil energy. There is a strong need for techniques to further discriminate the signal from the background. The measurement of the directions of the individual nuclear recoils would open the interesting possibility of correlating them with the velocity vector of the sun relative to the Galaxy. However, the length of typical recoil tracks is 20 nm in solids and 30 μm in low-pressure gas, and no detector has -yet- achieved the required spatial resolution with a sufficient mass and radiopurity [5]. A more subtle effect is provided by the contribution of the Earth orbital motion around the Sun to its radial velocity relative to the galactic center, resulting in an annual modulation of the WIMP flux of the order of a few % [2]. Exploiting this signature requires a very large detector mass and long exposure [6]. In the absence of a measurement of the constant part of the scattering rate, the interpretation of the modulated part depends on the details of the velocity distribution.

An important signature to establish its coherent aspect of the scattering and help establish the spin dependent or independent nature is the measurement of its dependence with A. This pleads for the simultaneous development of detectors with differing target nuclei. The comparison of different detectors with different systematics is also essential to confirm any discovery.

Many experiments significantly reduce the dominant background at low energy due to X and γ rays and to β decays by techniques differentiating the electron recoils produced by these processes from the sought-for nuclear recoils. It then remains to shield the experiment from the fast neutrons able to produce nuclear recoils with energies in the range of interest. In detectors with dimension larger than the $\sim$cm mean-free path of fast neutrons, this can be achieved by defining an internal fiducial volume (see e.g. K. Abe contribution to this conference). Alternatively, in large arrays of smaller detectors, neutron interactions can be tagged by coincidences. The discrimination between electron and ion recoils can be done by expoiting the different behavior of these particles as they slow down and stopped in the medium. The recoil energy is first converted in phonons and ionization, eventually producing scintillation light. In the end, all the energy that does not escape the detector or is not trapped in permanent defects is thermalized into low-energy phonons, producing a temperature increase. The relative yield of the three processes (phonon, ionization and scintillation) often differ for electron and nuclear recoils, and the simultaneous measurement of two of these signals can thus tag the nature of the recoil. A measurement of thermal phonons is truly calorimetric, and has a very small dependence on the recoiling particle [7]. It provides the most precise measurement of the recoil energy. Ionization and scintillation yields depend strongly on the nature or particle and can provide the needed discrimination. The combination of signals used by experiments having recently produced competitive WIMP limits are phonon and ionization (CDMS [8]), heat and ionization (EDELWEISS [9]), heat and scintillation (CRESST [10]) and ionization and scintillation (XENON [11], ZEPLIN [12]). Alternative electron/ion discrimination techniques involve pulse shape of scintillation signals, applicable for example in liquid argon and neon [13], and in CsI [14]. The experiments COUPP, PICASSO and SIMPLE [15], for their part, use the large linear energy loss of recoiling ions to trigger bubble formation in superheated liquids.

In the following, we will present the most recent results from the three experiments having achieved the best sensitivities for spin-independent interactions of WIMPs with masses above 10 GeV$\cdot$c^{-2} (see Fig. 1): XENON-100, CDMS II and EDELWEISS-2.

2. XENON-100

This experiment [11] uses the relative ionization and scintillation yields to discriminate electron and ion recoils in a two-phase volume of 170 kg of xenon. The target in the liquid phase is observed by an array of 98 and 80 photomultipliers (PMs), respectively at the top and bottom of the cylindrical container. These PMs detect the primary scintillation light (signal S1) due to the de-excitation of a meta-stable excimer efficiently produced in atomic collisions. Then, an intense electric field drifts the electrons produced in ionization processes toward the top surface where they are further accelerated in the gaseous phase, creating a secondary pulse of scintillation (S2)

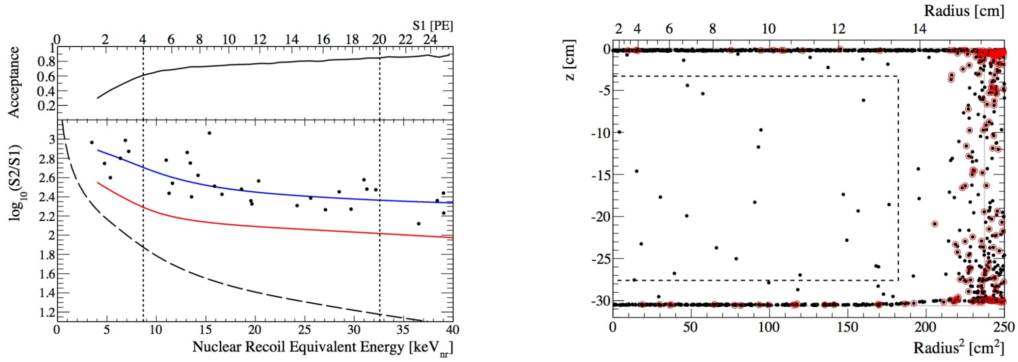

Figure 2: Left: Discrimination parameter versus recoil energy in XENON-100 (see text). The blue and red lines depicts the average ratio of the secondary signal to the primary signal (S2/S1) for electron and ion recoils, respectively. Right: corresponding radial and vertical coordinates of events in the same experiment.

proportional to the ionization yield. The average ratio (S2/S1) for electron and ion recoils differ by a factor ~ 0.4 over most of the relevant energy range (Fig. 2). The discrimination performances are limited by the statistics of scintillation photons (a 10 keV nuclear recoil correspond to a S1 of approximately 5 photoelectrons). The radial and vertical axis of the primary interaction are derived from the signal intensity in the different PMs and the time delay between the two pulses, respectively. Only events occurring in the inner fiducial volume of 40 kg are considered (right pannel of Fig. 2). Due to the high purity of the xenon, achieved by multiple purification cycles, and to the self-shielding capabilities of the detector shown in Fig. 2, the total events rate observed in the fiducial volume is two order of magnitude less than what was achieved with version the experiment, XENON-10, with a limited fiducial volume of 5 kg only. The data shown Fig. [11] has been collected following a test run of 11.2 live days. After selection cuts, this correspond to the observation of zero events in a fiducial exposure of 172 kg·d in the recoil energy range from 7.4 to 29.1 keV, resulting in the exclusion curve shown in Fig. 1. This technique provides the most stringent spin-independent limits for WIMP masses below 70 GeV$\cdot$c^{-2}. The experiment will acquire more data in 2010, with the goal of reducing the uniform background observed inside the fiducial volume (Fig. 2) with an improved purification of the xenon, and a sensitivity goal of 2×10^{-9}pb. A larger detector with 1 ton of xenon is in preparation for 2014, with a sensitivity goal of 3×10^{-11}pb. Other large-volume projects of noble-liquid detectors are also being considered in the coming years.

3. CDMS II

The experiment CDMS [8] uses an array of nineteen 250 g cryogenic germanium detector, with the simultaneous measurement of phonon and ionization signals. These detectors have two natural advantages: both phonon and ionization measurements have typical energy resolutions of one keV or less, and the radioactivity of hyperpure semiconductor crystals is extremely low. The ionization signal is collected using electrodes covering the surface of the crystal. The phonon signal is measured using an array of four quadrants of $\sim$1000 transition-edge tungsten sensors, covering one face of the detector. This system has a large acceptance to out-of-equilibrium phonons. As a result, the radial position of an interaction in the detector can be measured with a mm precision

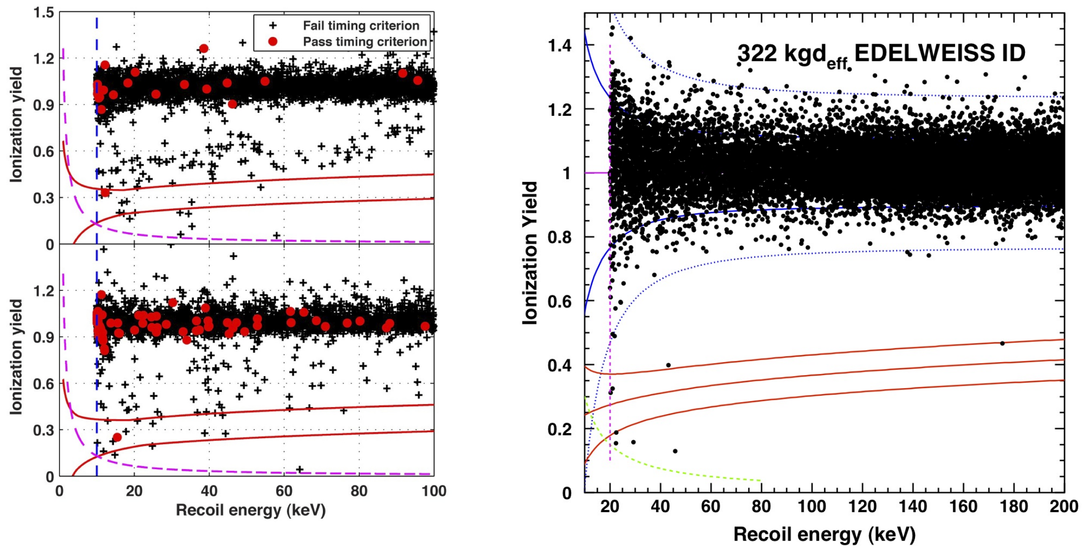

Figure 3: Left: Ionization yield versus recoil energy in the most recent CDMS data (see text). The data before and after the timing cut are shown as black crosses and red dots, respectively. Right: Ionization yield versus recoil energy for the EDELWEISS experiment.

using the relative size of the phonon signals in the four quadrants, enabling the energy of the event to be reconstructed with a keV resolution. The time structure of the build-up of the athermal signal is also measured. The phonon signal rise time and its delay relative to the fast ionisation signal are of the order of a few μs. These time constants are systematically larger for phonons associated with nuclear recoils, relative to those arising from electron movements. The detectors thus provide two independent discrimination variables for the identification of nuclear recoil: the ionization yield relative to the total calorimetric energy measured by the phonon sensor, and the time structure of the phonon signal. This double discrimination is important, since the ionization yield measurement is degraded for surface events, where a substantial fraction of the charge may be lost due to trapping and diffusion effects. CDMS has published the analysis of a last exposure of 192 kgd (after selection and fiducial cuts). Two nuclear recoil candidates are observed above their recoil energy threshold of 10 keV (left panel of Fig. 3), a result not entirely incompatible with the expected background of 0.8 events. Combined with the previous observation of zero candidates in an exposure of 121 kgd, this experiment provides the most stringent limits on spin-independent interactions for WIMP masses above 70 GeV$\cdot$c^{-2} (Fig. 1) The collaboration is preparing for the next generation of arrays of more massive detectors, with an interleaved electrode design (see next section) and with total germanium masses of 15 kg to 100 kg (SuperCDMS at Soudan in 2010 and at SNOLAB in 2012, respectively) and an eventual one-ton stage (GEODM at DUSEL, in 2017).

4. EDELWEISS

The experiment EDELWEISS [9] sets its most recent limits using an array of ten 400 g germanium cryogenic detectors, installed in the Laboratoire Souterrain de Modane (LSM). Like CDMS, its detectors use the ratio of the ionization yield to the phonon signal to identify nuclear recoils. Here, the phonon measurement is provided by a simple GeNTD thermistance, glued to the detector. The signal is purely thermal, with a uniform response over the entire detector volume. The rejection of events with incomplete charge collection is based on the ionization measurement. The electrodes on the flat surfaces of the cylindrical detectors are replaced by concentric, annular interleaved electrodes, with a pitch of 2 mm. With this "InterDigit" electrode design (ID), surface events are tagged by the presence of charge on two electrodes on the same side of the detector, resulting in a measured rejection factor for events due to the surface contamination by ^{210}Pb of $\sim 10^5$. At the end of 2009, the results from the first six months of this search were published [9]. An additional 8 months of data has been recorded since then, and processed using the same analysis and recoil energy threshold of 20 keV. It brings the total exposure to 322 kgd. The data are shown in the right panel of Fig. 3. Three nuclear recoil candidates are observed between 20.2 and 22.5 keV, and an additional one is observed at 175 keV. The resulting limits are shown in Fig. 1. It is the second most sensitive result for WIMP masses above 200 GeV$\cdot$c^{-2}. The number of observed candidates exceed the estimated background (<1.6 event at 90%CL). However, this is also the case of events lying close but outside the nuclear recoil band (Fig. 3). Following these observations, the detector design has been improved: the interleaved electrode pattern now covers the entire surface of the detectors, the total mass of the detector has been increased to 800 g, the fiducial volume has been segmented in two parts and a second thermal measurement has been added. Tests of these new detectors are under way, with encouraging results. The construction of an array of forty 800 g detector, to be completed by 2012, is in progress. Further developments are being studied in the framework of the EURECA [16] collaboration, aiming for an experiment in the future extension of the underground laboratory at LSM, with a sensitivity goal of 10^{-11}pb . This project brings together the European efforts of EDELWEISS and also of the CRESST and ROSEBUD teams working on heat-and-scintillation detectors, to built a ton-scale multi-target array of cryogenic detectors.

5. Searches beyond the Constrained SuperSymmetric Models

While models inspired by the type of SUSY models that will be probed at LHC provide the main thrust for the current searches, some recent findings have prompted the appearance of alternate models that are sometime best probed by experiments with alternative designs. For instance, in models where spin-dependent processes dominate over much-suppressed spin-independent one, there is a strong interest for a detector with a target atom with a large nuclear spin, such as ^{19}F [15]. There have been attempts to reconcile the observation of the annual rate modulation in DAMA with the stringent limits imposed by CDMS, XENON and many other experiments by invoking models where WIMPs have dominantly inelastic interactions [17]. This brought about alternative analyses of CDMS [8] and XENON [11] data. In another proposed model, the WIMP mass would be less than 10 GeV$\cdot$c^{-2} (lower than the LEP bounds for neutralinos), combined with the possibility - discarded by now [18] - that recoiling ions in NaI have a high probability for channeling. Another hint of a low-mass WIMP is the report by the CoGeNT collaboration of an excess rate below 2 keV in a ionization-only detector (corresponding to $\sim$9 keV if the reduced ionization yield for nuclear recoils is taken into account). This claim is being currently investigated by other experiments.

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6. Conclusions

Direct Dark Matter searches are crucial experiments to attest the presence of WIMPs in our environment, and provide a strategic complementarity with a possible observation of SuperSymmetry at LHC. The experiment is apparently simple, but the required extremely low backgrounds are quite challenging and foster constant technological innovations. The need for observations with a variety of targets material motivates intense world-wide efforts in R&D. The most sensitive technologies are, for now, cryogenic germanium detectors (offering good performances in terms of resolution and discrimination) and double-phase xenon detectors (offering large masses, self-shielding and low thresholds). New opportunities are arising with the projects for the extension and/or build up of large underground labs at DUSEL, LSM and JinPing.

References

[1] G. Jungman, M. Kamionkowski, and K. Griest, Phys. Rep. **267**, 195 (1996); G. Bertone, D. Hooper and J. Silk, Phys. Rep. **405**, 279 (2005).

[2] J.D. Lewin and P.F. Smith, Astropart. Phys. **6** (1996) 87.

[3] M. Vogelsberger et al., MNRAS **395** (2009) 797; A. Green, Phys. Rev. D *66* (2002) 083003; C. Savage, K. Freese and P. Gondolo, Phys. Rev. D **74** (2006) 043531; P. Ullio and M. Kamionkowski, Journal of High Energy Physics, Issue 3 (2001) 49.

[4] L. Roszkowski, R. Ruiz de Austri and R. Trotta, Journal of High Energy Physics, Issue 7 (2007) 075.

[5] S. Ahlen et al., International Journal of Modern Physics A **25** (2010) 1.

[6] R. Bernabei et al., Eur. Phys. J. C **67** (2010) 39.

[7] A. Benoit et al., Nucl. Instr. Meth. Phys. Res. A **577** (2007) 558 and references therein.

[8] Z. Ahmed et al., Science **327** (2010) 1619; and M. Kos oral contribution to this conference.

[9] E. Armengaud et al., Phys. Lett. B **687** (2010) 294; A. Broniatowski et al., PLB **681** (2009) 305.

[10] G. Angloher et al., Astroparticle Physics **31** (2009) 270.

[11] E. Aprile et al., Phys. Rev. Lett. **105** (2010) 131302.

[12] V. N. Lebedenko et al., arXiv:0812.1150 [astro-ph].

[13] M.G. Boulay and A. Hime, Astropart. Physics **25** (2006) 179; P. Benetti et al., Astropart. Phys. **28** (2008) 495, and M. Kos poster contribution to this conference.

[14] H.S. Lee et al., Phys. Rev. Lett. **99** (2007) 091301.

[15] E. Behnke et al., Science **319** (2008) 933; F. Aubin et al., New J. Phys. **10** (2008) 103017; M. Felizardo et al., Nucl. Instr. Meth. Phys. Res. A **589** (2008) 589.

[16] H. Kraus et al., J. Phys. Conf. Ser. **39** (2006) 139.

[17] S. Chang, G.D. Kribs, D. Tucker-Smith and N. Weiner, Phys. Rev. D **79** (2009) 043513; D. Smith and N. Weiner, Phys. Rev. D **64** (2001) 043502.

[18] N. Bozorgnia, G. B. Gelmini and P. Gondolo, JCAP **11** (2010) 019.

[19] C.E. Aalseth et al., arXiv:1002.4703v2.

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