WIMP direct detection overview

Y. Ramachers†
Oxford University, Denys Wilkinson Building, Physics Department, OX1 3RH Oxford, UK

Abstract

This review on weakly interacting massive particle (WIMP) dark matter direct detection focuses on experimental approaches and the corresponding physics basics. The presentation is intended to provide a quick and concise introduction for non-specialists to this fast evolving topic of astroparticle physics.

1 Introduction

There exists a large collection of measurements providing convincing evidence in favor of the existence of dark matter in the universe (reviewed by L. Bergstroem at this conference, see [1] and references therein). The nature of dark matter in the universe is among the most demanding questions in astroparticle physics. Dark matter refers to matter which is inferred astronomically only through its gravitational effects, and which neither absorbs nor emits sufficient electromagnetic radiation. Moreover, it is likely that the determination of its nature will yield new information in particle physics, since there is strong evidence that the dark matter is not composed of baryons but is rather in some exotic form [2]. One group of main candidates can be classified as weakly interacting massive particles (WIMPs). A particular candidate favoured from particle physics is the lightest supersymmetric particle (LSP), in most modern supersymmetric theories the neutralino. However, WIMP searches are not specialized to detect the neutralino but any particle with similar generic properties like a mass above a few GeV and weakly interacting with normal matter.

Currently many experiments try to reveal the existence and properties of WIMPs by their direct detection [3] (for indirect detection approaches, see [1]). Direct detection means to detect WIMP energy deposition by their elastic scattering off nuclei of specially designed low background detectors. Since WIMPs are assumed to compose the major part of the dark halo of our galaxy, the kinematical constraints determine the general requirements of such a detection technique. The details of WIMP direct detection will be outlined in the next section.

The current experimental status may be briefly summarized as follows: no WIMPs have been found so far - the first evidence for a WIMP detection from the DAMA collaboration [4] still lacks an independent confirmation of their result. The currently closest competitors to DAMA, the CDMS collaboration [5], EDELWEISS [6] and ZEPLIN [7] are so far not sensitive enough in order to fully test the announced WIMP-nucleon cross section versus WIMP–mass region by the DAMA collaboration. Even the most recent result by the EDELWEISS collaboration, first presented here at this conference, does not completely test the DAMA region taking into account all necessary assumptions for such a comparison (see below and the EDELWEISS presentation at this conference [8]). Finally, many new or upgraded experiments will soon reach a significantly improved sensitivity level for WIMP detection as will be outlined in this review. Chances are good to see an exciting year 2002/3 for the direct detection of dark matter particles.

*Invited review given at NEUTRINO 2002, Munich, Germany, May 25-30, 2002
†e-mail: yorck.ramachers@lngs.infn.it
2 WIMP direct detection physics concepts

From an experimentalists point of view, one might summarize the main characteristics of a direct detection experiment with three key-points.

**Energy threshold** as low as possible. Since the WIMP signal is expected to originate from elastic scattering, a featureless, quasi exponentially decreasing energy spectrum will result. The relevant energy region will be typically below 100 keV. Therefore, the lower the energy threshold, the more of the signal can be detected.

**Target mass** as high as possible. Since WIMP direct detection means a rare event search with total rates constrained by experiments to be roughly below 1 event per kg detector mass per day, one would need target masses generally above the kilogram scale in order to gain a sufficient statistic in a reasonable life-time of the experiment.

**Background** as low as possible. Two keynotes are worth to remember here as this is the major parameter for current WIMP direct searches. First, the signal is a nuclear recoil, i.e. a WIMP scatters elastically off a nucleus of the detector material thereby producing a nuclear recoil, which then deposits its energy in the detector. The operation of WIMP detectors in an underground laboratory using all the typical precautions of rare event searches (material selection, shielding) is mandatory. For nuclear recoil events a generic background contribution originates from neutrons. Second, the majority of background consists of electron recoils from photons (x-ray or gamma-ray radiation) or electrons (beta radiation). Any means to discriminate between these two types of recoil energy depositions automatically reduces the background significantly.

![Figure 1: The time-dependent WIMP direct detection signatures.](image)

Figure 1: The time-dependent WIMP direct detection signatures. The drawing on the left side displays the Earth orbit in galactic coordinates and the sun moves to the left with about 220 km/s, inducing a WIMP wind. The kinetic energy changes in summer compared to winter induce an annual modulation of count rates. The same WIMP wind induces additionally a strong asymmetry of nuclear recoil directions which would modulate on a daily basis as shown in the drawing on the right. The third signature, not displayed, is the target material dependence of the rate equation.

Most of the physics of WIMP direct detection can be described in detail by the WIMP-nucleus interaction rate equation (1), calculating expected counts per recoil energy, see also [10]:

$$\frac{dR}{dQ} = 2 N_T \frac{n_0 \sigma_0}{m_{\text{w}} r} F^2(Q) \int_{v_{\text{min}}}^{v_{\text{max}}} \frac{f(v)}{v} dv$$

(1)
This equation can be decomposed into various contributions from different fields of research, notably particle- and astro-physics. All numbers or functions described as belonging to "detector-physics" in Tab. 1 are assumed to be well known or possess minor uncertainties. Most of them are under control of the experimenter like the amount of target nuclei, \(N_T\), target nucleus mass, \(m_n\) and recoil energy \(E_R\). An important point to note about the recoil energy value is that for some types of detection techniques, see below, the measured energy value does not correspond to the deposited recoil energy. A detector–specific quenching factor, to be calibrated before, has to correct effects of ionisation losses of nuclear recoil events compared to electron recoil events.

### Table 1: Decomposition of the rate equation (1).

<table>
<thead>
<tr>
<th>Particle-Physics</th>
<th>Astro-Physics</th>
<th>Detector-Physics</th>
</tr>
</thead>
<tbody>
<tr>
<td>(m_w)</td>
<td>(n_0 = \rho_0/m_w)</td>
<td>(F^2(Q))</td>
</tr>
<tr>
<td>(\sigma_0)</td>
<td>(f(v))</td>
<td>(m_n)</td>
</tr>
<tr>
<td>(v_{max})</td>
<td></td>
<td>(N_T)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(E_R)</td>
</tr>
<tr>
<td>unknown</td>
<td>estimates</td>
<td>minor uncertainty</td>
</tr>
</tbody>
</table>

Figure 2: Classification scheme for WIMP direct detection techniques.

The form factor as a function of recoil energy, \(F^2(Q)\), has to be calculated specifically for a given target nucleus. It parametrises the loss of coherence of a WIMP interaction with a nucleus being an extended object. The form factor is an input from nuclear physics and a detailed treatment of it can be found in [9, 10].

The terms labelled "astrophysics" represent values and functions which are input from astronomy. These describe the source or location of WIMPs, i.e. the WIMP dark halo of our galaxy. The escape velocity, \(v_{max}\), determines the cutoff of the WIMP energy spectrum at high energies, typically...
below 100 keV, since its value being around 600 km/s. A more important parameter is the local halo density, $\rho_0$, since the WIMP signal is directly proportional to its value. This particular number represents rather an assumption than a reasonable guess. It is very uncertain, to a factor two or even more, since its value is strongly linked to the assumed halo model. The precise dark halo model would determine also the WIMP velocity distribution, $f(v)$. However, since any dark halo model is so far merely an assumption, both, the WIMP halo density and the WIMP velocity distribution represent a significant systematic uncertainty. The determination of a dark halo model is currently a very active topic of research in astrophysics ([11] and references therein). Meanwhile, the WIMP direct detection community uses a canonically assumed halo model, the simplest reasonable model fixing the density at a value of 0.3 GeV/cm$^3$ and assumes a Maxwellian velocity distribution for WIMPs.

The remaining two numbers in the rate equation are attributed to particle physics and are completely unknown. They characterize properties of the unknown WIMP, i.e. its elastic scattering cross
section, $\sigma_0$, and its mass, $m_w$. These are the numbers to be determined by direct detection experiments. Consequently, results of such experiments are given on the $\sigma_0$--$m_w$ plane. In fact, there exist two independent representations of results since in general a non-relativistic WIMP (moving in the galactic gravitational potential means to move non-relativistic for particle masses under consideration here) can couple to normal matter either coherently (scalar coupling) or to the spin of a nucleus (axial coupling) or both [9, 10, 12]. The coherent channel has been the most attractive so far since cross sections scale as nucleus mass squared (coupling to all nucleons equally). Therefore, for this spin-independent channel targets made of high mass nuclei are favoured. Besides the elastic scattering process, also inelastic scattering has been examined (for a review [10]) but this is beyond the scope of this article.

Direct consequences of the rate equation are the three WIMP signatures listed in the caption of Fig. 1. Two of them result from a time-dependence in the rate equation. The annual modulation signature originates from the revolution of the Earth around the Sun, as sketched in Fig. 1, left panel. This figure shows the Earth orbit in galactic coordinates, with the sun moving to the left according to the local rotation curve with about 220 km/s. The additional velocity (about 15 km/s) of the Earth revolution adds in summer and subtracts in winter [13], inducing mean kinetic energy changes for impinging WIMPs. The resulting count rate modulations as function of recoil energy are claimed to have been detected by the DAMA experiment, and consequently they announced evidence for WIMP detection [4]. No competing background process mimicking this signature has been identified so far.

The second time-dependent signature, the diurnal signature [14], can be exploited from detectors which are capable to measure the nuclear recoil direction. On average, this directionality of WIMP scattering events should be highly asymmetric with the majority of events pointing in the 'downwind' direction, i.e. anti-parallel to the Sun velocity vector. Due to the rotation of the Earth, this asymmetry would therefore be time-dependent, inducing a diurnal modulation of events.

Finally, as the third signature, the rate equation possesses a complicated dependence on the target material, i.e. on the target nucleus mass $m_n$. In case one could achieve sufficiently similar background conditions for two or more detectors which consist of different target materials, one might have the chance to measure the characteristic signal ratios, predicted by the rate equation. So far, no specific proposal exists to target this particular WIMP signature, however, it might turn out that it could be successfully applied by the cryogenic detector technology (see below and for the signature [15]).

### 3 WIMP direct detection techniques

The three minimal requirements of low threshold, reasonably high target mass and ultra-low background for WIMP direct detection experiments seem to constrain detector technology quite significantly. Nevertheless, a large variety of ingeniously designed detectors currently search for WIMP dark matter or will start measurements soon. An almost complete classification scheme can be inspected in Fig. 2. Note that although it is meant to be as general as possible, at least four experiments or experiment proposals do not quite fit into this scheme. These will be mentioned at the end of this section.

Three general detection principles for nuclear recoil energy depositions are shown in Fig. 2: ionisation, scintillation and phonon detection, where phonon detection symbolizes the cryogenic detector technology. Among these three, only scintillation detectors offer an intrinsic nuclear recoil discrimination mechanism by pulse shape analysis. This is one of the main reasons for these detectors to be among the most sensitive experiments for WIMP searches, notably the DAMA, UKDMC NaI [16] and the ZEPLIN I liquid Xenon experiment.

The DAMA experiment deserves a special note at this place since it is the only experiment which announced an evidence for WIMP detection [4]. All other experiments gave upper limits on WIMP-nucleon cross sections as function of WIMP mass (usually to 90% C.L.). The WIMP signature DAMA claims to see is the annual modulation of count rates, see Fig. 3. So far, no alternative explanation of
Figure 5: Some selected spin-independent exclusion limits including the DAMA evidence region. To the right, the figure legend is displayed.

the measured characteristics (consistent modulation parameters, only count rates at threshold, 2 keV, to 6 keV visible energy show the modulation) has been proposed. Consequently, the WIMP evidence remains essentially unchallenged except for other experiments trying to constrain the cross section – mass region with upper limits.

The experiments utilizing ionisation detectors are considered to be 'classical' Germanium semiconductor experiments. However, the implication of 'classical' meaning 'old-fashioned' must be rejected. The collected experience in operating such detectors under ultra-low background conditions combined with new ideas for their design offers an interesting future despite the fact that strong nuclear recoil discrimination capabilities are not available. For example, the proposed large mass experiments, MAJORANA [17] and GENIUS [18] (or its approved test facility, GTF [19]) will reduce their background by completely new shielding designs, which will then allow to reduce background further by an efficient anti-coincidence measurement between several detector modules. Due to the relatively large target mass, tens to hundreds of kilograms of Germanium, they will also be able to use the annual modulation signature as a WIMP-induced nuclear recoil discrimination procedure.

Pure cryogenic detectors like CRESST I [20], Rosebud [21] or the Tokyo LiF [22] setup do not offer an intrinsic discrimination. They are nevertheless important to establish low background cryogenic detector facilities or test specifically very low mass WIMPs\(^1\) due to their unprecedented low thresholds [20]. One important property of such detectors to note is their apparently 100% quenching factor [24], i.e. the phonon channel measures energy depositions from nuclear recoils like electron recoils. This allows CRESST I to constrain a possible WIMP signal at recoil energies as low as 600 eV (corresponding to 195 eV for a Germanium detector threshold, 180 eV and 54 eV for a sodium recoil and an iodine recoil respectively in a NaI crystal; for quenching factors, see [25, 26]).

Apart from the above mentioned 'pure' technology experiments, most efforts on WIMP detection focus on 'mixed' detectors, see Fig. 2, offering two instead of one information-readout channels. Common to these exciting technologies is their strong nuclear recoil discrimination capability. Again three alternative approaches exist: combining light and ionisation readout - ZEPLIN II and III [27], phonon

\(^1\)which may become interesting again as shown in [23]
and light readout - CRESST II [28] and Rosebud and phonon and ionisation readout - CDMS and EDELWEISS.

The family of ZEPLIN experiments (up to a proposal for ZEPLIN-MAX, a one ton ZEPLIN II extension) uses liquid Xenon as target material, a high mass nucleus. The ZEPLIN II and III detectors use in addition to the liquid scintillator signal the ionisation produced in the liquid to drift the released charge out of the liquid into the gas phase. There they measure the secondary scintillation in the gas either in a low drift-field mode or in a high drift-field mode. Since the ionisation due to electron recoils is much more efficient in liquid Xenon compared to nuclear recoils, an event–by–event discrimination becomes possible for total target masses of up to 30 kg (ZEPLIN II). Besides ZEPLIN, similar projects have been proposed, XENON [29], or are under construction, XMASS [30].

The cryogenic phonon–ionisation experiments CDMS and EDELWEISS are operative already and give the sharpest constraints so far on WIMP spin-independent cross sections. They use Germanium and (CDMS) Silicon semiconductor crystals to collect the phonon signal and the ionisation signal (applying a small bias of about 6 V) simultaneously. The quenching factor then yields two distinctive branches of events as function of energy in both readout channels. Electron recoils produce the same energy output in the ionisation as in the phonon channel\(^2\). Ionisation from nuclear recoils instead is quenched, so that only the phonon channel shows the true deposited energy. The collaborations encountered a problem arising from incomplete charge collection, which can mimic a nuclear recoil (less ionisation than expected from an electron recoil). This appears to have been solved at least to a degree that they now give the most stringent limits of all direct WIMP searches. In addition, the approach of the CDMS collaboration to use Germanium and Silicon crystals in a common setup offers the chance to discriminate for the first time between nuclear recoils due to neutrons and WIMP events.

The combined light–phonon readout means to employ a scintillator crystal, cooled to cryogenic temperatures (about 15 mK for the CRESST setup [28]). Since scintillation measurements need some light-sensitive device, such a detector module has to involve two cryogenic detectors. One is a scintillating crystal with a phonon readout thermometer. The second is an extreme low threshold detector, a thin, large area crystal (between 4 and 16 cm\(^2\) have been tested) in a light-tight setup. The low threshold condition comes from the maximum light output of CaWO\(_4\) crystals, which is at around 400nm wavelength corresponding to about 3 eV. Fig. 4 shows one of the new CRESST II detector modules. Two main advantages compared to the previous technologies can be stated. First, the larger collection of different potential target materials since there are many candidate scintillators with efficient light output at the required low temperature. That, however, is still subject to extensive research by the collaboration. Second, the apparent independence of surface effects like incomplete charge collection as for the semiconductor approach. The scintillator volume is fully active without dead-layers and no need exists to define the active volume. The event-by-event discrimination involves again the quenching factor. The phonon channel measures deposited recoil energy whereas the light channel is quenched for nuclear recoil events.

One might envision for such a technology to apply several different target materials in a common setup to utilize the material signature of WIMP events. The CRESST collaboration currently prepares to upgrade their experiment for a total target mass of 10 kg CaWO\(_4\) scintillators. First results using a single or two new detector modules of the type shown in Fig. 4 (about 300 g CaWO\(_4\) single crystal) are expected soon.

Finally, there exist experiments and proposals which are not included into the scheme of Fig. 2. Two of them use the high dE/dx of nuclear recoils to discriminate against background, notably the SIMPLE [31] and the PICASSO [32] experiments. Metastable liquid droplets immersed in a gel expand (explode) due to a phase transition to the gaseous phase in case a particle or nucleus with sufficiently high energy deposition over unit length interacts in the liquid. The threshold for such

\(^2\)After a known correction due to the Luke effect, which describes phonon production due to drifting charges in the crystal.
a bubble explosion can be fine-tuned by pressure and temperature controls. The main advantage of such integrating detectors is that they can be tuned to be almost background-blind. They would not react on electron recoils and alpha-radiation events while being fully sensitive to nuclear recoils either by fission products, neutrons or WIMPs above a definite threshold. However, this detector type does not deliver more energy information than the threshold. Obtaining an energy spectrum would be a tedious procedure. One would have to vary threshold energies step–by–step.

Then there exists another inspiring idea, the CASPAR proposal [33]. The idea is to use the short range of nuclear recoil events compared to electron recoils in order to discriminate between the two. Small granules of scintillating crystals are immersed in a liquid scintillator. A long range background event then has a high probability to excite both scintillators which would be visible by pulse shape analysis. Nuclear recoils instead should only show the characteristic light-output of the crystalline scintillator.

Finally, a special sort of ionisation detector shall be mentioned, the DRIFT experiment [34]. Although it uses pure ionisation in a gas as detection principle it deserves a special place among the WIMP detectors. The emphasis here is on ionisation tracks which are measured with a multi-wire proportional chamber in a low-pressure gas. Therefore it represents the first operating nuclear recoil-direction sensitive experiment. It is in fact the only experiment (in principle) capable of observing the strong diurnal modulation. The main drawback, however, is obvious by the term 'low-pressure', i.e. the low target mass. Nevertheless, the track recognition also implies a strong background discrimination by recoil range. An expansion of the experiment into the kilogram mass scale is planned.

4 Conclusion

The general aim would be to build a ton-scale experiment in order to explore orders of magnitude lower cross sections. However, as can be inspected in Figs. 5, 6, even with the most promising technologies it is a long way to gain factors in sensitivity. So far, no experiment has ever measured below the $10^{-6}$ pb level ($10^{-42}$ cm$^2$) for spin-independent interactions. It is not known, which kind of systematics will appear for a given detector when probing an order of magnitude below. It would certainly represent
already a big leap for the field if an experiment could reach the $10^{-7}$ pb level. The point is that simple scaling of existing technologies will not be sufficient as unknown or so far unstudied effects might become dominant sources of background. Dedicated studies beforehand of thinkable extreme rare events would certainly help to decide for a detector technology to scale-up for a large experiment. A first study in this direction, for example, has been undertaken by the EDELWEISS collaboration [35].

Besides these efforts, one should bear in mind that the DAMA evidence still is neither excluded nor confirmed. Therefore it might turn out as well that experiments encounter an irreducible 'background' simply being WIMPs. In that case, building an experiment with a sensitivity between the $10^{-6}$ to $10^{-7}$ pb level would produce in fact a high signal-to-noise WIMP spectrum which can be studied in detail. Such a sensitivity level is promised for the next round of experiments like CRESST II, CDMS, EDELWEISS and the ZEPLIN family among others. Therefore, it might be that in the near future an exciting discovery of dark matter particles could be announced.

Inspecting Fig. 5, one might question the statements from above as the new EDELWEISS limit seems to exclude practically the whole DAMA evidence region to 90% C.L. However, this impression is misleading. Such a figure provokes a combination of experimental results 'by eye' but the only statistically justified combination of experimental results in this case would be by multiplication of the corresponding likelihood functions (see e.g. [37]). Such a comparison or combination of results has not been undertaken. Toy model studies [38], however, suggest that such an operation would rather lead to a new evidence region, incorporating the EDELWEISS result as a new constraint.

In summary, the present situation for direct WIMP dark matter searches is very promising with a lot of upcoming results from diverse detector technologies in the near future.

References


the same is true for the most recent ZEPLIN I limit [36].
References

DATA listed top to bottom on plot
NAIAD 2002 result
IGEX 2002 limit
ZEPLIN I, 2002 result
CDMS Mar. 2002, Qshared, bkgd subtracted, no Si data
DAMA 2000 58 kg−days NaI Ann. Mod. 3sigma, w/o DAMA 1996 limit
Edelweiss, 11.7 kg−days Ge 2000+2002 limit
DATA listed top to bottom on plot
- TOKYO, Spin Dependent Exclusion Limit, LiF 15m w.e.
- CRESST spin dep. limit, 1.51 kg days, 262g sapphire
- DAMA Xe129
- UKDMC NaI, from combined Na and I data