WIMP/NEUTRALINO DIRECT DETECTION

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The most popular candidate for non baryonic dark matter is the neutralino. More than twenty experiments are dedicated to its direct detection. This review describes the most competitive and promising experiments with different detection techniques. The most recent results are presented with some prospects for the near future.

1 Introduction

The existence of dark matter in the Universe is now well established in the astro-particle community reinforced by the recent astrophysical observations of the satellite experiment WMAP\(^1\) : about 27% of the mass-energy of the Universe is composed of matter. Ordinary matter (baryons) contributes to about 4% of this total mass density of the Universe and only \(\approx 1\%\) is visible according to the most recent measurements of the amount of deuterium in high red-shift clouds of gas and of the CMB\(^2\). Hence about 90% of this dark matter is not baryonic. We have to distinguish two categories, hot and cold dark matter particles referring to their velocity at the matter-radiation decoupling time in the early Universe. Hot dark matter implies moving relativistically and cold moving non-relativistically. Neutrinos with non-zero masses are hot dark matter candidates, however WMAP\(^1\) results combined with other experiments and observations lead to a contribution \(< 1.5\%\) for light neutrino species.

So the bulk of the non-baryonic dark matter is cold dark matter (CDM). Among the numerous solutions proposed by theorists axions and neutralinos are favorites. Neutralinos are candidates of the generic class of Weakly Interacting Massive Particles (WIMP). Axion are particles proposed to solve the strong CP violation problem in the Peccei-Quinn theory \(^3\). Astrophysical considerations combined with experimental constraints require an axion mass in the range \(10^{-3}\) to \(10^{-6}eV/c^2\). For a more detailed discussion about axions see reference\(^4,5,6\), since this paper will be dedicated to the WIMP/neutralino detection. The neutralino is the lightest supersymmetric particle, a linear combination of the supersymmetric partners of the photon, Z and Higgs bosons, in the minimal supersymmetric extension of the standard model:

\[
\chi^0 = a\tilde{\gamma} + b\tilde{Z} + c\tilde{H}_1^0 + d\tilde{H}_2^0
\]  

(1)

Its mass is constrained to lie in the range \(45\text{ GeV} < m_\chi < 3\text{ TeV}\), where the lower bound comes from accelerator results from LEP and the upper bound is given by astrophysical constraints such as the age of the Universe or unitarity. Locally our galaxy is supposed to be imbedded in a WIMP halo.

Many experiments are dedicated to direct and indirect detection of WIMPs, two complementary techniques. Direct detection experiments measure the energy deposited by elastic scattering of a neutralino of our own galaxy off a target nucleus. For masses larger than \(\approx 200\text{ GeV}\), indirect detection of dark matter particles through their annihilation products may be more suitable. In this paper we will concentrate on the case of direct detection techniques, and for a complete description of indirect approaches we refer to the papers\(^7-12\).

In the direct detection approach the expected event rate depends on various parameters coming from astrophysics, particle physics and nuclear physics; it can range from 1 to \(10^{-5}\) events/kg/day. The measured signal is very low (few keV) depending on the masses of the incident particle and of the scattered nucleus, but also on the nuclear recoil relative efficiency (quenching factor) in producing charges, light or heat. Hence WIMP direct searches put strong constraints on experimental background environments, and require detectors with very low energy thresholds. In this review we present the different possible signatures for disentangling a WIMP signal from the background. Different experimental approaches are described and illustrated by a few experiments. The current limits in the exclusion plot and near future prospects will be also presented.
2 WIMP/neutralino direct detection physics principles

As mentioned previously, WIMP-nucleus interaction rate depends on various parameters. First we have to define a WIMP halo model. For simplicity the approximation of a maxwellian velocity distribution in the galactic frame is made \( \text{(see 13 for a review on alternative halo models)} \). Next, a supersymmetric model is chosen for predicting the WIMP interaction with quarks of nucleons inside the target nucleus. Depending on the chosen model the WIMP-nucleus cross-section has two components\(^{14,15} \): spin-dependent and spin-independent. The spin-independent term couples to the mass of the nucleus and the spin-dependent couples to its spin. The nuclear form factor depends on the nature of the interaction. The spin-dependent case is the most complicated one, requiring detailed nuclear models (for more details see dedicated papers\(^{15,17} \)). In the following we will restrict this review to the simplest spin-independent case which is supposed to dominate in most models for massive target nuclei. Taking into account these previous considerations the interaction rate can be expressed as follows:

\[
\frac{dR}{dQ} = \frac{\sigma_0 \rho_h}{2m_r^2m_\chi} F^2(Q) \int_{v_{\text{min}}}^{\infty} \frac{f(v)}{v} dv \tag{2}
\]

where \( m_r \) is the WIMP-nucleus reduced mass \( m_\chi m_N/(m_\chi + m_N) \), \( m_\chi \) is the WIMP mass, \( m_N \) is the nucleus mass.

\( \rho_h = 0.3 GeV/c^2/cm^3 \) is the assumed halo WIMP density at the position of the solar system, \( f(v) \) is the dark matter velocity distribution, with an average rms velocity \( v_0 = 220 km/s \), truncated above the escape velocity of the galaxy \( v_{\text{esc}} \approx 575 km/s \), \( \sigma_0 \) is the total nucleus-WIMP interaction cross section and \( F(Q) \) is the nuclear form factor.

2.1 Exclusion plot \( \sigma(m_\chi) \)

In order to reliably compare supersymmetric models with results obtained by different experiments using different techniques a \( \sigma_0(m_\chi) \) plot is built in the following way. The cross-sections \( \sigma_0(m_\chi) \) are normalized to a single nucleon \( \sigma(m_\chi) \) to allow comparisons between different target nuclei. The measured nuclear recoil event rate is compared to a theoretical spectrum calculated for a given WIMP mass and cross-section. If an experiment observes a signal then we build a \( \sigma(m_\chi) \) contour plot. If the observed events cannot be unambiguously associated with a WIMP signal an exclusion limit is calculated. WIMP signals have distinctive signatures that backgrounds are not supposed able to mimic. Three different signatures are proposed.
2.2 Annual modulation

As a result of the Earth motion around the Sun the count rate in detectors should show an annual modulation (fig. 1). Along the year the Earth’s velocity relative to the galaxy varies, as in June the Earth and the Sun velocities add up whereas in December they subtract\(^1\). The maximum amplitude of this effect in the signal is about 7%. We will report later that the DAMA collaboration using NaI scintillating crystals is the first experiment and at the moment the only one, claiming for an evidence of a WIMP annual modulation signal.

2.3 Diurnal modulation and directionnality

Another possible modulation in the WIMP signal is the night and day variation, this effect is due to the shielding of the detector by the Earth of the incident flux. For masses close to 50 GeV and under certain assumptions the diurnal modulation can be larger than the annual one\(^16\). However the most interesting daily signature coupled with the annual one is the directionnality of the WIMP wind as illustrated in figure 2. This effect is also larger than the annual one. The validation of the principle has been performed by the DRIFT-I experiment with a 1 m\(^3\) low pressure TPC\(^19\) prototype.

2.4 Target atomic mass effect

Observed together annual and diurnal modulations are unambiguous methods to distinguish WIMP and background signals, but they are very difficult to operate. In the spin-independent case, an easiest method is to use different target materials as the event rate depends on the target atomic mass. To give an estimate of this effect we can use the Smith and Lewin\(^14\) calculated integral rate \(R_0\) with no form-factor correction and an average recoil energy \(E_R\)

\[
R_0 \simeq 5.87 \times v_0 \sigma_{m^1} \rho_h A^3 \frac{m^2}{(m^1 + m^2)^2} / kg/d \quad (3)
\]

\[
E_R \simeq 2 \times 10^{-6} m^2 \left(\frac{v_0}{c}\right)^2 \frac{m_A}{(m^1 + m^2)^2} keV \quad (4)
\]

Table 1 reports on \(R_0\) and \(E_R\) values for different targets, and for a given WIMP mass of \(m^1 \simeq 50\) GeV, \(\sigma m^1 \simeq 7 \times 10^{-6}\) pb. Naively if we consider the event rate it seems to be more advantageous to use high mass nuclei, but if we look to the recoil energy as the target atomic number \(A\) increases, the average deposited energy tends to decrease. So the choice of a target is a compromise between these two quantities. Moreover we can see for example that germanium is more efficient than silicon for WIMPs detection while they have similar cross-sections for neutrons.

Another important point is the possible neutron multiple scattering in the detector, which is impossible for a WIMP. We will see hereafter this method is used by the CDMS collaboration\(^20\), with germanium and silicon targets as illustrated in figure 6.

### Table 1. Integrated event rate \(R_0\) and average energy deposition for different target atomic masses, no form-factor correction and \(m^1 = 50\) GeV, \(v_0 = 220 km/s\) and \(\sigma m^1 = 7 \times 10^{-6}\) pb.

| \(A\) | \(R_0\) | \(< E_R >\) |
|-----|-------|-------|
| H   | 5.10\(^{-5}\) | 1     |
| Na  | 0.3   | 11    |
| Si  | 0.5   | 12    |
| Ge  | 3     | 13    |
| I   | 8     | 11    |
| Xe  | 9     | 11    |
| Pb  | 18    | 8     |

3 WIMP/neutralino direct detection techniques

WIMP detectors are constrained by three important requirements : low threshold, ultra low background and high mass detector. When a WIMP interacts with a nucleus, the nuclear recoil can induce different signals (fig. 3) : heat, ionization and scintillation. During the last decade important technical developments were based on one or two of these different physics processes.

3.1 Quenching factor

A relevant parameter in WIMP direct detection is the relative efficiency of nuclear recoil called quenching factor. It is the ratio of the number of charge carriers produced by a nuclear recoil due to the WIMP
interaction over an electron recoil of the same kinetic energy (electron equivalent energy or "eee"). For scintillating materials the quenching factor is defined as the ratio between the light produced by a nuclear recoil and by an electron recoil.

While in conventional detectors this factor is usually below 30% (measured, e.g. to be \( \approx 0.3 \) for germanium\(^{21} \), \( \approx 0.25 \) for sodium and \( \approx 0.08 \) for iodine\(^{22} \)), for cryogenic detectors described hereafter it has been measured to be around one for recoiling nuclei independently on energy\(^{23,24,25} \).

### 3.2 Classical detectors: semiconductors and scintillators

Germanium diodes initially used in double beta decay experiments were the first detectors used to search for WIMPs, since they have very low thresholds and very good resolutions. Experiments like IGEX\(^{26,27} \) and HDMS\(^{28} \), with about 2 kg of enriched \(^{76}\)Ge, achieved very low background count rates \( (<0.2 \text{evt/kg/day in the interval 10-40 keV}) \) and \( E_{\text{thr}} \approx 4 - 10 \text{keV-ee} \) (equivalent to \( \approx 15 - 30 \text{keV recoil} \)).
Large masses were easily achievable with scintillators like NaI or liquid xenon in a very pure environment. The DAMA experiment has operated more than 100 kg of NaI (each crystal weighting about 9.7 kg with energy threshold of \( \simeq 2\text{keV} - ee \) to 22 keV recoil) for several years in the Gran Sasso underground laboratory. They accumulated data during 7 years and since 1997 they announce evidence for an annual modulated WIMP signal. The DAMA group claim their observation is compatible with a signal induced by a WIMP of \( \simeq 52\text{ GeV} \) mass ad a WIMP-nucleon cross section of \( \simeq 7\times 10^{-28}\text{pb} \). The DAMA collaboration has published an update of this last summer the last 3 years campaign totalizing 7 years and confirms their observation of an annual modulation signal as illustrated in figs. 4,5. Right now none of the currently running dark matter experiments confirms this signal as we can see in the current exclusion plot in fig. 9. Independent experiments with NaI detectors (NAIAD in the Boulby mine, ANAIS in Canfranc, ELEGANT in Oto Cosmo Observatory) are currently running. The NAIAD experiment most recent results begin to exclude the DAMA \( \sigma(m_\chi) \) region in the spin-independent exclusion plot.

As we have seen previously despite the very high purity level of classical detectors, they suffer ultimately from a lack of power discrimination between electron and nuclear recoils.

The first discrimination method used is based on a pulse shape analysis. It is a statistical method where the measured quantity is the rise-time of the light signal which depends on the nature of the recoiling particle. This discrimination method is used with sodium iodide crystals (DAMA, NAIAD) but is also successfully used with liquid scintillators like liquid xenon.

With a 3.1 kg liquid-Xenon detector the ZEPLIN-I collaboration has reached preliminary sensitivities which could exclude the DAMA zone. However some problems remain : a relatively high electronic background rate has to be understood, there’s no nuclear recoil calibration for the low energy part of the spectrum (<50 keV-ee), a poor energy resolution compared to bolometers. Some of these points should be answered in the next few months as the experiment in now currently running deep underground in the BOULBY mine.

The DAMA/LIBRA collaboration is currently running a new NaI detector with a larger mass (\( \simeq 250\text{ kg} \)) as well as a liquid-Xenon detector.

The future projects ZEPLIN-II and -III aimed to be able to develop a discrimination technique with a two phase liquid-gas Xenon detector with charge and light signals.

### 3.3 Cryogenic detectors

Since the beginning of the 90’s important developments were also made in new directions like cryogenic detectors. They are made of a crystal with a thermometer glued on it, operating at very low temperature (few tens of millikelvin). Very low thresholds were reached by the CRESST-I experiment with a 262 g sapphire calorimeter (resolutions of \( \simeq 133\text{ eV} \) at 1.5 keV and thresholds \( \simeq 500\text{ eV} \)).

But most impressive results were obtained with mixed techniques allowing the simultaneous measurement of two components heat-light or heat-charge. The two combined informations are a powerful tool to distinguish a nuclear recoil induced by a WIMP or a neutron interaction from electron recoils induced by a gamma or an electron interaction (quenching factor described previously). It is an event by event discrimination method. Again different approaches were explored by different worldwide collaborations. For cryogenic detec-
The CDMS collaboration was the first to operate a detector giving simultaneously ionization and heat signals with a germanium crystal. Until 2002 the experiment was running in the shallow site in Stanford with a poor muon shielding inducing an important neutron background. Despite this limitation they derive competitive dark matter limits and were leaders for several years. They could subtract the neutron background using a monte carlo simulation but also taking advantage of the fact that they run simultaneously two different targets: germanium and silicon. During the year 2003 the CDMS-II experiment is being installed in the deep underground Soundan mine where the muon flux is reduced by 5 orders of magnitude reducing the neutron background by a factor 400. They are currently operating 2 towers (fig. 6) of 3x165 g Ge and 3x100 g Si detectors and 18 more detectors are under fabrication totalizing 4 kg of germanium. The CDMS collaboration expects to improve its current sensitivity ($\approx 1$evt/kg/day) by two orders of magnitude.

The currently best spin-independent published limit was obtained by the EDELWEISS collaboration.
Figure 9. Current spin-independent limits for the most competitive experiments. The WIMP halo parameters used are \( \rho_h = 0.3 \text{GeV/cm}^{-2}\text{cm}^{-3} \), \( v_0 = 220 \text{km/s} \). The closed contour corresponds to the 3\( \sigma \) allowed region of the DAMA first four years obtained with the same WIMP halo parameters.

The EDELWEISS experiment is installed in the underground laboratory of Modane in the French-Italian Alps. They operate similar detectors to those of CDMS germanium crystals (fig. 7) with different technologies for the electrodes running at \( \simeq 18 \text{mK} \). Three 320 g detectors are running simultaneously. During the last campaign in June 2003, 2 events were observed in the nuclear recoil zone which origin is under investigation. More data is being analysed, but the EDELWEISS-I stage data taking will be soon finished. For the next stage a larger cryostat with a detection volume of 100 litres is built and is currently being tested. This cryostat benefits from an original technology developed at the CRTBT-Grenoble laboratory. The EDELWEISS-II installation will take a year from now. The first step will operate 21x320 g germanium detectors with NTD thermometers and 7x200 g NbSi thin film germanium detectors developed by the group of the CSNSM laboratory. A muon veto made of 140 m\(^2\) plastic scintillator will be added. It should reject the neutron background induced by cosmic muons in the inner lead shielding, which has been evaluated two orders of magnitude below the present EDELWEISS-I sensitivity \( \simeq 0.2 \text{evt/kg/day} \). Such background has to be clearly identified and rejected since the expected event rate for the EDELWEISS-II stage is about \( 10^{-2} \text{evt/kg/day} \). In a second step up to 120 detectors will operate simultaneously.

The CRESST-II\(^{44}\) and ROSEBUD\(^{43}\) experiments involve scintillating crystals as cryogenic detectors. They operate in the same way: the heat is measured with thermometer glued on the scintillator and the light is collected with a second thin but large surface crystal. The main advantage of such method is the large possibility for scintillating target materials: CaWO\(_4\), PbWO\(_4\), Al\(_2\)O\(_3\), BaF, BGO, ... and for important volumes. A few years ago S.Pécourt et al.\(^{42}\) characterized the phonon channel of a 1 kg Al\(_2\)O\(_3\) bolometer and recently the same team\(^{43}\) has succeeded in measuring the light output of a 50 g Al\(_2\)O\(_3\) bolometer (fig. 8).

The CRESST-II\(^{44}\) experiment should operate 33x300 g modules of CaWO\(_4\) totaling about 10 kg.

3.4 New promising techniques

In addition to the techniques described above, illustrated by currently running experiments and their near future, other promising techniques are under investigation.

The PICASSO\(^{45,46}\) and SIMPLE\(^{48}\) experiments have choosen to adapt a well known technology used in neutron dosimetry, to develop a counter for WIMP induced nuclear recoils. The method is based on small superheated Freon droplets imbedded in a gel matrix at room temperature. The nuclear recoil of \( ^{19}\text{F} \) induces the explosion of a droplet, creating an acoustic shock wave measured with piezoelectric transducers. By varying the temperature of the gel the energy threshold can be triggered in such a way...
Figure 11. DRIFT-I ionization tracks for three different types of recoiling particles: argon, helium and electrons.

way that the electron recoil induced by gamma background can be suppressed. Calibration is made at different pressures and temperatures with monoenergetic neutrons produced by a Van de Graaff Tandem. The use of $^{19}\text{F}$ (spin-$1/2$ isotope) is particularly interesting to search for spin-dependent neutralinos. A first generation of detectors, 16 modules of 8 ml, lead to the published limit of the PICASSO collaboration$^{45,46}$. They are currently running the second generation of modules with a larger volume (fig. 10)) in an improved low background environment in the SNO underground laboratory: PIC@SNO. New purification techniques were developed especially for the PICASSO experiment$^{47}$. Despite a very good background discrimination the main disadvantage of such an integrating detector is the necessity to run the experiment at different threshold energies in order to measure the deposited energy spectrum.

To take advantage of the directionality which appears as the clearest signature of WIMPs, the UKDMC collaboraton has developed and is currently running successfully, the DRIFT-I detector. It consists in a 1 m$^3$ low pressure TPC filled with a $\text{Xe} - \text{CS}_2$ gas mixture. The principle of the TPC is well known, the innovation is the use of $\text{CS}_2$ negative ions instead of $\text{e}^-$ as charge carriers reducing the diffusion in order to achieve millimetric track resolution (fig. 11). Important improvements on the read-

out techniques such as MICROMEGAS$^{35}$, in order to increase the pressure hence the target mass, are underway. Other possible target gases are also studied to prepare the next generations DRIFT-II and -III with a larger gas mass for the TPC of the order of 100 kg.

4 Conclusions

The current experimental spin-independent limit turns around $10^{-6}$ pb which corresponds to a count rate of about 0.2 to 1 evt/kg/day. To achieve this limit it took about 10 years for most of the currently running first generation experiments to develop these detectors. The next generation under construction and for most of them on the final stage, aim to improve this limit by two orders of magnitude, that means a count rate around $10^{-2}$ evt/kg/day. This has a price: lowering the sensitivity by about two orders of magnitude implies increasing the target mass by about the same factor (for example EDELWEISS-I worked with 3x320 g Ge and EDELWEISS-II should run at the end 120x320
g Ge detectors).

With this scaling the ultimate neutron background induced by muons can no longer be neglected. It is the reason why experiments like EDELWEISS-II, CDMS-II and CRESST-II will use a muon veto.

The next five years are very promising: a clarification of the DAMA annual modulation signal is essential. Indirect Earth-based and Space experiments like Antares, HESS, AMS and GLAST should give independent cross checks. Meanwhile accelerator physics will explore an important part of SuSy space parameters on the exclusion plot (fig. 12).

Nevertheless the one-tonne scale experiment will probably involve larger international collaborations. The technical challenge will be to build an experiment able to achieve the extremely low background necessary to cover most of the prediction mSUGRA models.

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