DIRECT AND INDIRECT DETECTION OF WIMPS

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Abstract

We present here the principles of detection of Weakly Interacting Massive Particles, which could represent a large contribution to Dark Matter. A status of the experimental situation is given both for indirect and direct detection. In particular, the DAMA claim for a WIMP signal is confronted to the recent results of the CDMS and EDELWEISS experiments. We conclude by comparing direct and indirect search sensitivities.
1 Introduction

Recent astrophysical observations of the Cosmic Microwave Background \(^1\) \(^2\) and high-redshift Supernovae \(^3\) \(^4\) tend to favor a Universe where matter is mainly dark \(^5\) (that is to say, not emitting electromagnetic radiation). Dark Matter may be present at galactic scale under the form of a halo composed of weakly interacting, massive \(-\text{more than 10 GeV/c}^2\) particles, the WIMPs. These hypothetical relic particles from an early phase of the Universe could be the Lightest Supersymmetric Particles of SUSY models (probably the neutralino) under the hypothesis of R-parity conservation. Two techniques have been proposed to put WIMPs in evidence: indirect and direct detection. Indirect detection consists in looking for by-products of WIMP-pair annihilation in cosmic-rays, while direct search looks for an interaction of a WIMP from the galactic halo with a terrestrial target. We will present and compare principles and results of both techniques here. A more complete review of the subject is given elsewhere \(^6\) \(^7\).

2 Indirect detection

In Minimum Supersymmetric Models, neutralinos are Majorana particles and therefore pair annihilations are possible and could be detected through their by-products: \(\gamma\) rays, positrons, antiprotons or neutrinos, to list the ones of experimental interest. Here, we will focus on neutrinos, since it seems to be, at this point, the candidate for which the experimental signature would be the most telling.

2.1 Principle of neutrino detection

Muon neutrinos can be produced by WIMP-pair annihilation directly or through decay of a lepton or a hadron pair with a typical energy of the order of the third to the half of the mass of the WIMP, and thus in the tens to hundreds GeV/c\(^2\) range. Their most significant production sites would be the center of the Earth or of the Sun. Indeed, they are the only regions where the WIMP density \(-\text{enhanced by gravitationnal capture}\) might be high enough to give consequent reaction rates, though Gondolo and Silk \(^8\) have shown that there may also be a significant amplification of the WIMP-annihilation rate at the center of our Galaxy. A neutrino can be detected through the upward-going muon produced in the core of our planet in a charged-current reaction. Having the information on the neutrino’s source (the muon is pointing to it) and a lower limit on its energy (given by the energy of the muon), it is possible to select the high energy neutrinos from WIMP-
pair annihilation originating from the Sun or the center of the Earth. A large part of the background noise is thus discarded (solar neutrino energies are for example typically of the order of 20 MeV/c²), and the only remaining sources of background are atmospheric neutrinos produced on the other side of our planet and neutrinos produced by cosmic-ray interaction in the corona of the Sun.

2.2 Results and perspectives

The first results on indirect WIMP search came in the eighties from detectors developed for other purposes, like the study of the proton decay (IMB), or the study of solar or atmospheric neutrinos (Baksan, Kamiokande, MACRO, etc). They were thus not totally adapted to WIMP detection (detection areas of the order of 10³ m²), but already provided limits on the upward-going muon flux 9) 10) interesting enough to reject the MSSM models for WIMPs yielding the largest neutralino rates. High-energy neutrino telescopes (ANTARES 11) or AMANDA 12) for example) are now under development. Large sizes should be achievable (up to the km², which corresponds to a factor 10⁴ improvement with regard to previous neutrinos detectors), since a natural medium is used as their detecting volume (water of the Mediterranean sea for ANTARES, ice of the Antarctic for AMANDA). Despite a higher energy threshold, their sensitivity to WIMP annihilation in the Sun or in the Earth is expected to be improved by the same 10⁴ factor, which corresponds to a muon flux of the order of 10 per km² per year for an exposure of 10 km².yr 13). This sensitivity should allow these experiments to test a large part of the domain allowed by MSSM models in the coming years.

3 Direct detection

3.1 Principle

Another possibility to put WIMPs in evidence consists in looking for the scattering of a WIMP from the galactic halo on a target detector placed on Earth, in which it would produce a nuclear recoil. This type of search can be readily extended to WIMP models beyond the MSSM since the only necessary condition for detection is a non-zero WIMP-nucleon cross-section. In the hypothesis where the WIMP is the MSSM neutralino, Goodman and Witten have shown 14) that it could couple to a quark of the scattered nucleus via two mechanisms: spin-dependent (Z-boson or squark exchange) or spin-independent (Higgs bosons or squark exchange). It can be shown 15) that the spin-dependent cross-section $\sigma_{SD}$ is proportional to the
nucleus spin $J$ of the target, while the spin-independent cross-section $\sigma_{SI}$ is grossly proportional to the square of the atomic number $A$ of the nucleus. It follows that $\sigma_{SI} > \sigma_{SD}$ for $A > 30$ (which corresponds to a large majority of the targets) and that the interaction rate per kg of matter varies between 1 event per day to one per decade, depending on model parameters and target nuclei. The two main requirements for direct search detectors are thus low radioactive background rates and, since WIMPs induced nuclear recoils are below 100 keV, low energy thresholds.

A positive signature could come from the annual modulation of the event rate in the detector. Indeed the relative velocity of the Earth with regard to the galactic halo varies annually with the rotation of the Earth around the Sun. Thus there should be a small variation of approximately 5% in the WIMP event rate in the detector. A significant experimental signature would nevertheless require large target masses ($\geq 100$ kg) and an excellent stability of the detector performances -better than the percent-, even under the extremely favorable hypothesis of the absence of background and for the SUSY models yielding the largest neutralino rates.

Several different solutions have been proposed to fulfill the heavy constraints of direct detection. We will present here those giving at this point the best results, even if some other innovative techniques seem promising.

### 3.2 Classical detectors

Historically the first type of detectors used for direct detection were germanium ionisation detectors at liquid nitrogen temperature. The interaction is detected through the collection of the charge of the electron-hole pairs created in the crystal. Thanks to years of development in the fields of $\gamma$ and $\beta$ spectroscopy and high performance germanium purification technique, Ge diodes can reach excellent energy resolutions (typically 1 keV full width half maximum for 300 keV deposited) and the lowest total event rate of all direct search experiments (0.042 event/kg/keVee/day between 15 and 40 keV recoil). Nevertheless, it is not possible to discriminate nuclear recoils (induced by neutrons or WIMPs) from electron recoils (induced by $\beta$ and $\gamma$ radioactivity), which is the dominant background. Therefore, the experiments using this technique (HDMS, IGEX, etc.) after holding the most stringent limits on WIMP-nucleon cross-section for a long time, seem now to be limited by this absence of rejection, even if projects using this type of detectors could remain competitive in the future.

Scintillators are other classical detectors adapted to WIMP direct detection. Large masses are achievable (730 kg for Elegant-V, 100 kg for DAMA). A statis-
tical rejection of the $\gamma$ background is possible using the different scintillation time constants between electrons and nuclear recoils (pulse shape discrimination), but this cannot be applied at energies just above threshold $^{22)}$ (typically below 5 keV), which correspond to the most significant part of the data. The best spin-dependent limit on the WIMP-nucleon cross-section has been achieved by the DAMA experiment using NaI crystals $^{22)}$, thanks to the non-zero spin of the sodium nuclei. Recently, the DAMA experiment also claimed an annual modulation signal $^{23)}$ which this group has attributed to a WIMP of mass $52^{+10}_{-8}$ GeV and a spin-independent WIMP-nucleon cross-section of $\sigma_n = (7.2^{+0.4}_{-0.3}) \cdot 10^{-6}$ pb. If combined to their 1996 exclusion data based on pulse shape discrimination $^{22)}$, the most likely WIMP mass and WIMP-nucleon cross-section values become respectively $44^{+10}_{-8}$ GeV and $\sigma_n = (5.4^{+1.0}_{-1.0}) \cdot 10^{-6}$ pb. This result remains controversial $^{6)} 24)$ and is hardly compatible with the results of other experiments $^{25)} 26)$ using a new type of detectors, bolometers.

3.3 Bolometers

3.3.1 Principle and Performances

Bolometers measure the elevation of temperature due to an interaction of a particle in an absorber (Saphire $^{27}$, Germanium $^{28}$, or CaWO$_4$ $^{30}$ for example) by means of a thermometric sensor glued to its surface. In principle, energy deposits as small as 1 keV result in a measurable elevation of temperature -typically 1 $\mu$K- in a 100 g detector working at a temperature of 10 mK. The elevation of temperature due to an energy deposit in the absorber is indeed inversely proportional to its heat capacitance, which is very small at these temperatures. Furthermore the fundamental resolution of such bolometers, given by thermodynamic fluctuations in the energy of the absorber, is in the tens of electron-volt range.

In the field of Dark Matter Search, bolometers offer another very attractive feature, since it is possible to reject electron recoils with a high efficiency for certain types of absorber. The number of charges created in a semiconducting absorber (Germanium or Silicon) by nuclear recoils is indeed approximately three times lower than for an electron recoil of the same energy. By measuring simultaneously the ionisation and the heat signals for every interaction, the CDMS and EDELWEISS $^{28)}$ experiments can thus discriminate $\gamma$ and $\beta$ radioactive backgrounds from possible WIMP-induced events with a rejection factor higher than 99% (see fig.1). The ROSEBUD $^{29}$ and CRESST $^{30}$ experiments have shown that the measurement of the scintillation light emitted in CaWO$_4$ absorbers also makes this discrimination possible. This active
Figure 1: Plot of the Ionisation/Recoil ratio ($Q$) against the recoil energy for events recorded in a $^{252}$Cf calibration run of the Edelweiss 320 g bolometer. The solid lines represent the average $Q$ distribution for photons ($Q=1$ by construction) and for neutrons ($Q = 0.16(E_{\text{Recoil}})^{0.18}$), and the dashed curves are the limits of the 99.9% efficiency regions for photons and neutrons.

rejection of the background explains why bolometers have the lowest nuclear recoil rates of all direct search experiments. It is also the reason why they are already competitive with the optimized classical detectors mentioned above, although still in their development phases.

3.3.2 Results

Recently, the Cryogenic Dark Matter Search (CDMS) experiment reported results obtained with three 165 g Ge heat-and-ionisation detectors. In 96 live days of data acquisition in their shallow site of Stanford (corresponding to 10.6 kg.days), they recorded 13 nuclear recoils in the 10-100keV recoil range. This rate is compatible with that expected from a WIMP of mass 52 GeV and a WIMP-nucleon cross-section of $7.2 \cdot 10^{-6}$pb. Nevertheless, the presence of 4 multiple-scatter nuclear recoils in the Germanium detectors and event rates measured with a 100 g Si cryogenic detector tend to favor the hypothesis where these 13 events are due to cosmic-ray induced neutrons. By making this assumption and subtracting the neutron background,
Figure 2: Plot of the Ionisation/Recoil ratio ($Q$) as a function of the recoil energy from the data collected in the centre fiducial volume of the 320g EDELWEISS detector. Also plotted are the $\pm 1.645\sigma$ bands (90% efficiency) for photons and for nuclear recoils. The 99.9% efficiency region for photons is also shown (dotted line). The hyperbolic dashed curve corresponds to 5.7 keV ionisation energy and the vertical dashed line to 30 keV recoil energy.

CDMS then obtained a limit for the WIMP-nucleon cross section incompatible with the whole $3\sigma$ region of the DAMA claim at 84% CL (see fig.3). The French experiment EDELWEISS, based in the underground site of the Laboratoire Souterrain de Modane (LSM), is not limited by the cosmic-ray induced neutron background so far, and may resolve this discrepancy. More recently, EDELWEISS has accumulated an effective exposure of 4.53 kg.days (fiducial volume) with a 320 g heat-and-ionisation Ge detector and observed no nuclear recoils in the 30-200 keV energy range (see fig.2). This excludes at 90% CL the central value obtained for the WIMP signal reported by DAMA with a WIMP-nucleon cross-section $\sigma_n = 7.2 \cdot 10^{-6}$ pb, but not the central value of $\sigma_n = 5.4 \cdot 10^{-6}$ pb, when the 1996 DAMA-NaI0 exclusion limit is taken into account (see fig.3). More data is thus needed by EDELWEISS to test the whole DAMA zone. This should come with the installation of three 320 g bolometers in the LSM, scheduled at the end of this year.
4 Conclusion: indirect vs direct detection

It is of course very tempting to compare the sensitivities of direct and indirect WIMP searches. This will be done here in the MSSM framework used in refs 13, 32) in which no restriction is brought from supergravity other than gaugino mass unification.

The muon flux due to the annihilation of WIMPs in the Earth depends on the density of the WIMP halo, its kinematics and the accretion rate of WIMPs in the Sun or the Earth, which itself is determined by the way WIMPs scatter off the nuclei composing the core of the Earth (mainly iron or nickel). This scattering is mainly spin-independent (since iron and nickel are heavy elements) and it is thus quite similar to the interaction taking place in direct detection experiments. Furthermore, the local halo density plays the same role in both cases. Therefore similar assumptions can be made for indirect and direct detection, and it is possible to link a given muon flux due to WIMPs annihilation in the core of the Earth to a certain WIMP-nucleon cross-section. This was done elsewhere 13), and the result, shown in fig.4, is that the sensitivities for spin-independent interactions expected for the future high-energy neutrinos telescopes (10 muons/km$^2$) are roughly equivalent to the present direct detection experiments limits on WIMPs-nucleon cross section ($\sigma_{SI} \simeq 10^{-6}$ pb).

For the case of muons coming from the Sun, the situation is quite different, since WIMPs interact with protons during the accretion phase. In the MSSM framework, it is thus the spin-dependent cross section which may become predominant, and the process is quite different from the one taking place in a direct detection detector. The comparison is thus more difficult. Nevertheless, calculations from ref. 13) show that the future high-energy neutrinos telescopes may in this case give better results than the present direct detection experiments (fig.4). Indeed the direct detection best spin-dependent WIMPs-nucleon cross section ($\sigma_{SD} \simeq 10^{-1}$ pb 22)) corresponds to a muon flux from the Sun that is several orders of magnitude higher than the 10 muons/km$^2$ expected from high-energy neutrinos telescopes, and already much larger than the limits derived from the Kamiokande observations.

A similar study led in ref. 15) comes to the same conclusion, which tends to prove that both methods are complementary and thus worth pursuing.
Figure 3: WIMP-nucleon spin-independent cross-section as a function of WIMP mass. Light solid curve: Limit obtained by EDELWEISS with the 70g bolometer data (28). Dark solid curve: Limit obtained by EDELWEISS with the 320g bolometer data (26). Dashed curve: combined Ge diode limit (16, 17, 18). Dash-dotted curve: 1996 DAMA-NaI0 limit using pulse shape discrimination (22). Light dotted curve: CDMS limit without statistical subtraction of the neutron background (25). Dark dotted curve: CDMS limit with statistical subtraction of the neutron background (25). Dark closed contour: allowed region at 3σ CL for a WIMP r.m.s velocity of 270 km/s from the DAMA annual modulation data (23). Filled circle: central value of the previous 3σ region (WIMP-mass 52 GeV and WIMP-nucleon cross-section $\sigma_n = 7.2 \cdot 10^{-6}$ pb). Light closed contour: allowed region at 3σ CL from the DAMA annual modulation data (23) when combined to their 1996 exclusion limit (22) and accounting for the uncertainty on the WIMP velocity (210-330 km/s rms). Triangle: central value of the previous 3σ region (WIMP-mass 44 GeV and WIMP-nucleon cross-section $\sigma_n = 5.4 \cdot 10^{-6}$ pb) for a WIMP r.m.s velocity of 270 km/s.
Figure 4: a): Muon flux from the Earth as a function of spin-independent neutralino-nucleon cross-section expected from different models of neutralinos. Dotted line: 3σ limit expected on muon fluxes from high-energy neutrinos telescopes with a 10 km$^2$.yr exposure. Dash-dotted line: present best limit on spin-independent neutralino-nucleon cross-section of direct detection experiments $^{25}$. b): Muon flux from the Sun as a function of spin-dependent neutralino-nucleon cross-section expected from different models of neutralinos. Dotted line: 3σ limit expected on muon fluxes from high-energy neutrinos telescopes with a 10 km$^2$.yr exposure. The present best limit on spin-dependent neutralino-nucleon cross-section of direct detection experiments ($\sim 10^{-1}$ pb $^{22}$) is too large to be shown on this plot. Taken from Bergström et al. $^{13}$. 
References


29. P. de Marcillac, private communication.

