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 reenforced 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 about 4% of this total mass density of the Universe and only $\simeq 1\%$ 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). Axions 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. More detailed discussions about axions can be found in papers listed in the References.[4−6] This paper will be dedicated to 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:

$$\chi^0 = a\tilde{\gamma} + b\tilde{Z} + c\tilde{H_1^0} + d\tilde{H_2^0}. \tag{1}$$

Its mass is constrained to lie in the range 45 GeV $< m_\chi <$ 3 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 $\simeq$ 200 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. For a complete description of indirect approaches we refer to other papers listed in the References.[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 charge, 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.

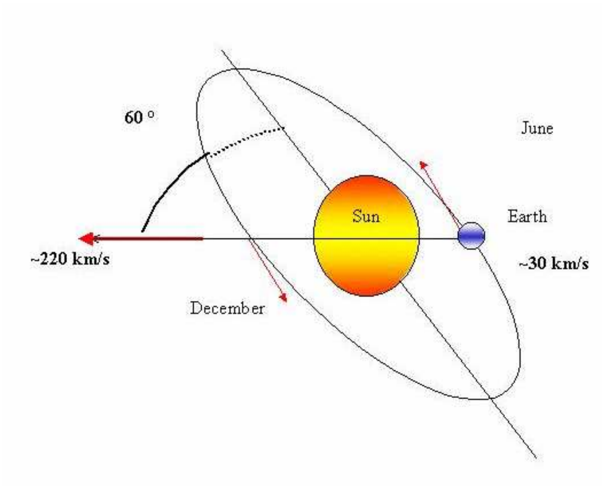

Figure 1. Annual modulation.

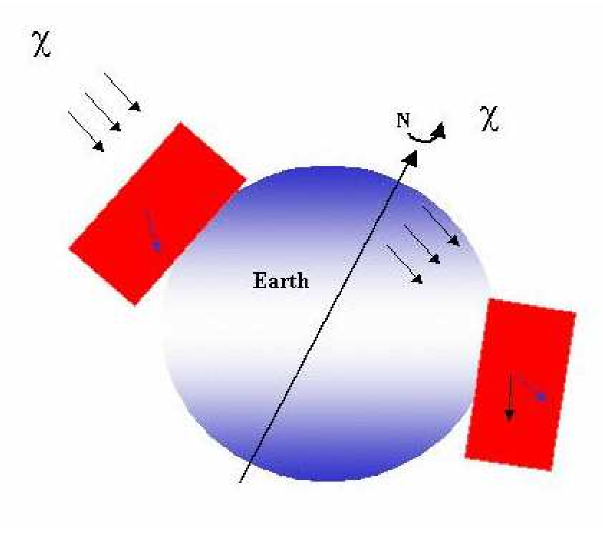

Figure 2. Diurnal modulation.

2. WIMP/Neutralino Direct Detection Physics Principles

As mentioned previously, the 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 (see Kamionkowski and Kinkhabwala (1998)[13] for a review on alternative halo models). Next, a supersymmetric model is chosen for predicting the WIMP interaction with quarks of the 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 :

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

where m_r is the WIMP-nucleus reduced mass $m_\chi m_N/(m_\chi + m_N)$, m_χ is the WIMP mass, and 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 r.m.s. velocity $v_0 = 220$ km/s, truncated above the escape velocity of the galaxy $v_{esc} \simeq 575$ km/s, and σ_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 unambigously associated with a WIMP signal an exclusion limit is calculated. WIMP signals have distinctive signatures that backgrounds are not supposed to be 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). The Earth's velocity relative to the galaxy varies, in June the Earth and the Sun velocities add up whereas in December they subtract.[18] 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 evidence of a WIMP annual modulation signal.

2.3. *Diurnal Modulation and Directionality*

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 from 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 directionality of the WIMP wind as illustrated in Fig. 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 unambigous methods to distinguish WIMP and background signals, but they are very difficult to see. In the spin-independent case, the 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:

$$R_0 \simeq 5.87 \times v_0 \sigma_{m_\chi} \rho_h A^3 \frac{m_\chi}{(m_A + m_\chi)^2} \text{ /kg/d}, \quad (3)$$

$$E_R \simeq 2 \times 10^{-6} m_\chi^2 (\frac{v_0}{c})^2 \frac{m_A}{(m_A + m_\chi)^2} \text{ keV}. \quad (4)$$

Table 1 shows R_0 and E_R values for different targets, and for a given WIMP mass of $m_\chi \simeq 50$ GeV and $\sigma_{m_\chi} \simeq 7 \times 10^{-6}$ pb. Naïvely if we consider the event rate it seems to be more advantageous to use high mass nuclei, but looking at 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

Table 1. Integrated event rate (R_0) and average energy deposition ($< E_R >$) for different target atomic masses (A), with no form-factor correction and $m_\chi = 50$ GeV, $v_0 = 220$ km/s and $\sigma_{n\chi} = 7 \times 10^{-6}$ pb.

	A	R_0	$< E_R >$
H	1	5.10^{-5}	1
Na	23	0.3	11
Si	28	0.5	12
Ge	73	3	13
I	127	8	11
Xe	131	9	11
Pb	210	18	8

more efficient than silicon for WIMP 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 Fig. 6.

3. WIMP/Neutralino Direct Detection Techniques

WIMP detectors are constrained by three important requirements: low threshold, ultra low background and a 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%

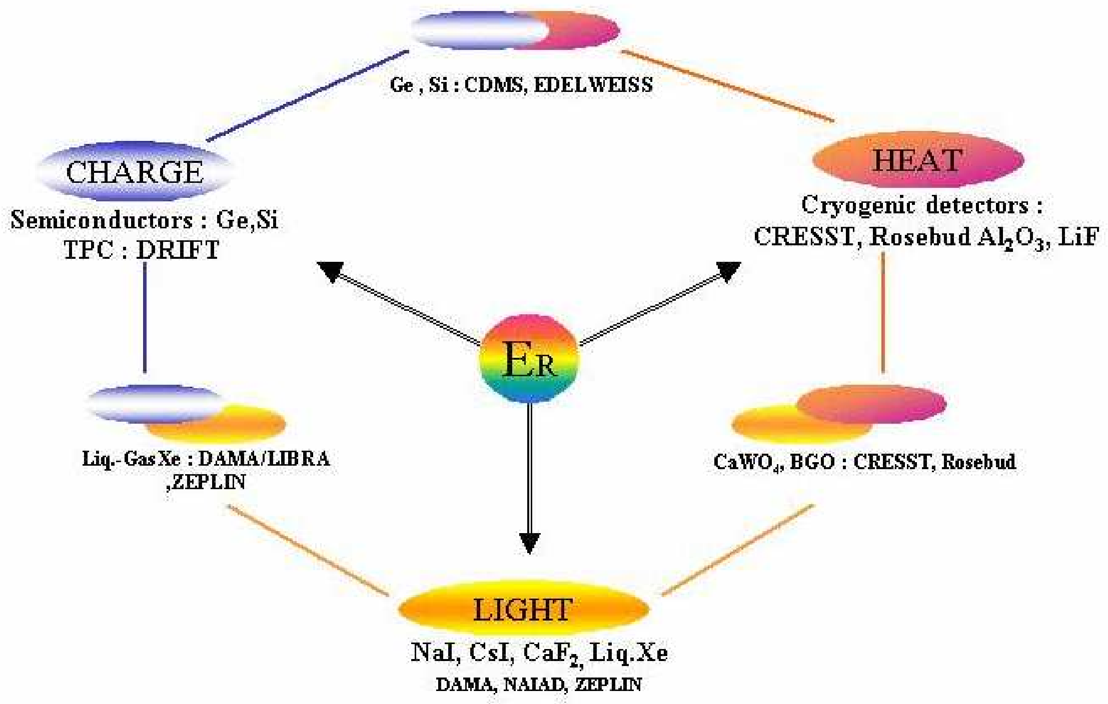

Figure 3. Illustration of the different techniques developed for the WIMP direct detection.

(e.g. measured to be $\simeq 0.3$ for germanium,[21] $\simeq 0.25$ for sodium and $\simeq 0.08$ for iodine[22]), for cryogenic detectors described hereafter it has been measured to be around one for recoiling nuclei independent of energy.[23−25]

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 evt/kg/day in the interval 10-40 keV) and $E_{thr} \simeq 4-10$ keV-ee (equivalent to $\simeq 15-30$ 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 $\simeq 2$ keV-ee, i.e. 22 keV recoil) for several years in the Gran Sasso underground laboratory. They accumulated data during the last 7 years and in 1997, after 4 years of data taking, they announced evidence for an annual modulated WIMP signal. The DAMA group claim their observation is compatible with a signal induced by a WIMP of $\simeq 52$ GeV mass and a WIMP-nucleon cross section of $\simeq 7.2$ pb. The DAMA collaboration has published[29], this last summer, the last 3 years campaign totaling 7 years and confirms their observation of an annual modulation signal as illustrated in Figs. 4 and 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[30] in the Boulby mine, ANAIS[32] in Canfranc, ELEGANT[33] in Oto Cosmo Observatory) are currently running. The NAIAD[31] experiment's 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.

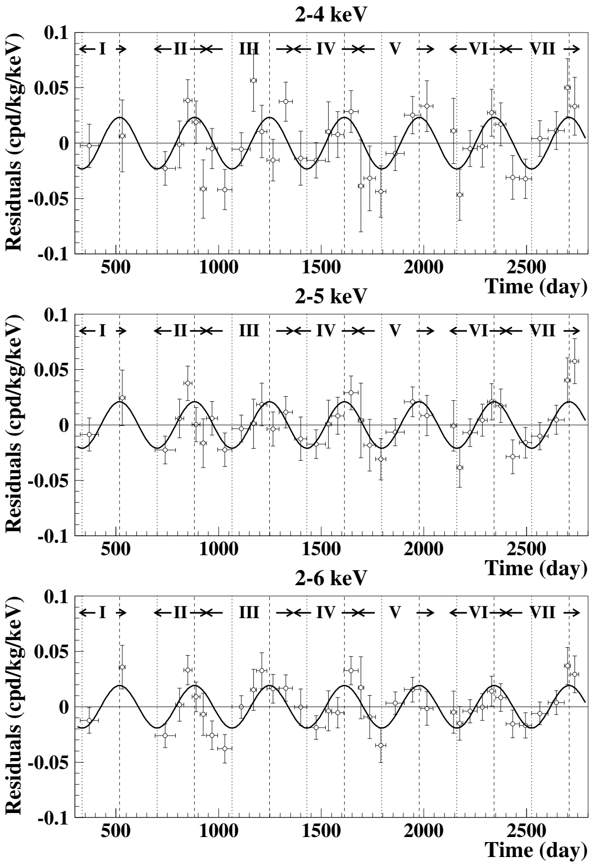

Figure 4. DAMA model independent residual count rates as a function of time for 7 years and three energy intervals (2-4), (2-5) and (2-6) keV-ee.

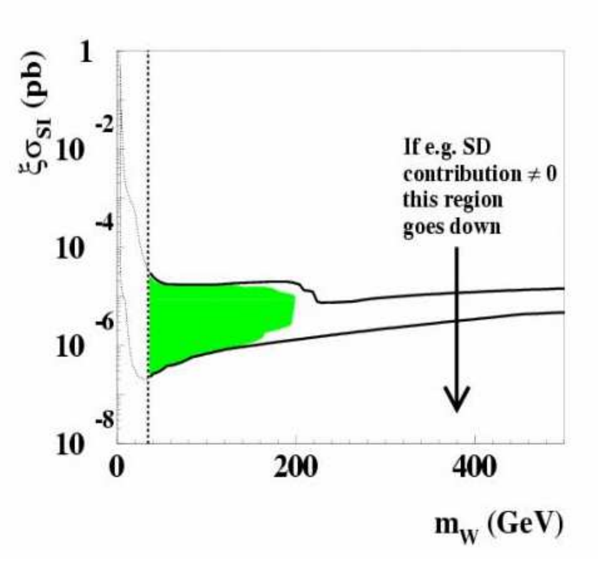

Figure 5. Dama limit for the dominant spin-independent case obtain with 7 years of data taking. This contour plot is obtained with different WIMP-halo models, see Bernabei *et al.*[29] for a detailed discussion.

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[34] 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 is no nuclear recoil calibration for the low energy part of the spectrum (<50 keV-ee), and 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.[14]

The DAMA/LIBRA collaboration is currently running a new NaI detector mith a larger mass ($\approx$ 250 kg) as well as a liquid-Xenon detector.

The future projects ZEPLIN-II and -III aim 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 milli-Kelvin). Very low thresholds were reached by the CRESST-I experiment[36] with a 262 g sapphire calorimeter (resolutions of $\simeq$ 133 eV at 1.5 keV and thresholds $\simeq$ 500 eV).

The most impressive results were obtained with mixed techniques allowing the simultaneous measurement of two components heat-light or heat-charge. The two combined observables 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 detectors the CDMS and EDELWEISS collabora-

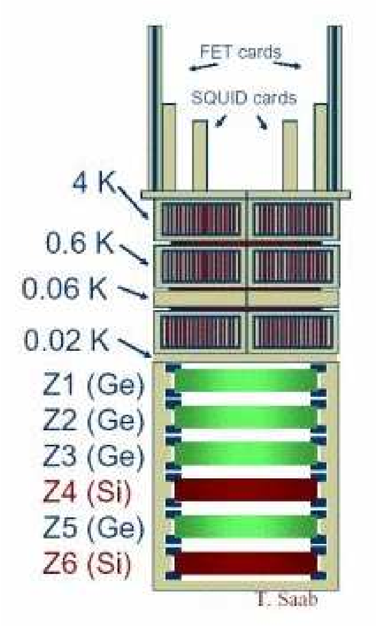

Figure 6. CDMS detector tower.

tions investigate the heat-ionization way, and the CRESST and ROSEBUD collaborations explore the heat-light channels.

The CDMS collaboration was the first[37,38] 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 poor muon shielding inducing an important neutron background. Despite this limitation they derived competitive dark matter limits and were leaders for several years. They could subtract the neutron background using a Monte Carlo simulation and also take advantage of the fact that they run si-

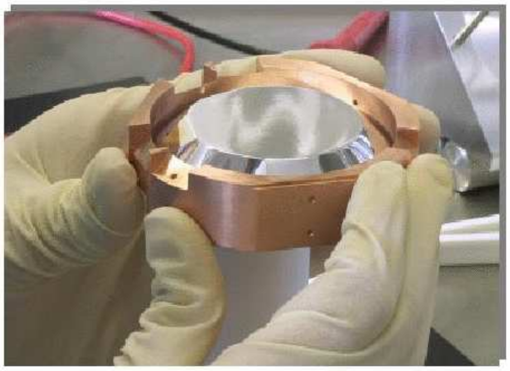

Figure 7. EDELWEISS 320 g Ge detector.

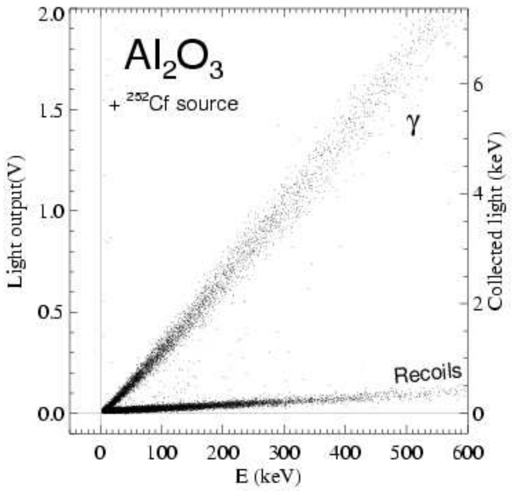

Figure 8. Discrimination between gammas and nuclear recoils in a 50 g sapphire bolometer at 20 mK by the ROSEBUD collaboration.

multaneously two different targets: germanium and silicon.[20,39] During the year 2003 the CDMS-II experiment is being installed in the deep underground Soudan mine where the muon flux is reduced by 5 orders of magnitude, thereby reducing the neutron background by a factor 400. They are currently operating 2 towers (Fig. 6) of 3×165 g Ge and 3×100 g Si detectors and 18 more detectors are under fabrication totaling 4 kg of germanium. The CDMS collaboration expects to improve its current sensitivity ($\simeq 1$ evt/kg/day) by two orders of magnitude.

The currently best spin-independent published limit was obtained by the EDELWEISS collaboration cumulating 32 kg-d. 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[40] running at $\simeq 18$ mK. Three 320 g detectors are running simultaneously. During the last campaign in June 2003, 2 events were observed in the nuclear recoil zone whose origin is under investigation. More data is being analysed, but the EDELWEISS-I stage data taking will soon be 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 place a year from now. The

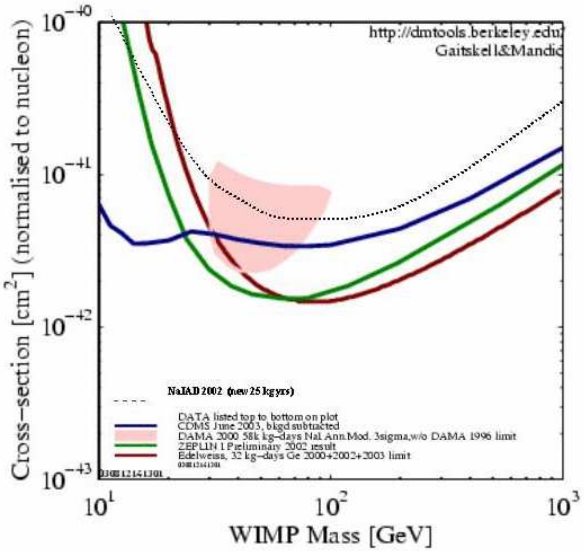

Figure 9. Current spin-independent limits for the most competitive experiments. The WIMP halo parameters used are ρ_h = 0.3 GeV/c^{-2}cm^{-3}, v_0 = 220 km/s. The closed contour corresponds to the 3σ allowed region of the DAMA first four years worth of data obtained with the same WIMP halo parameters.

Figure 10. PICASSO new 1 liter module.

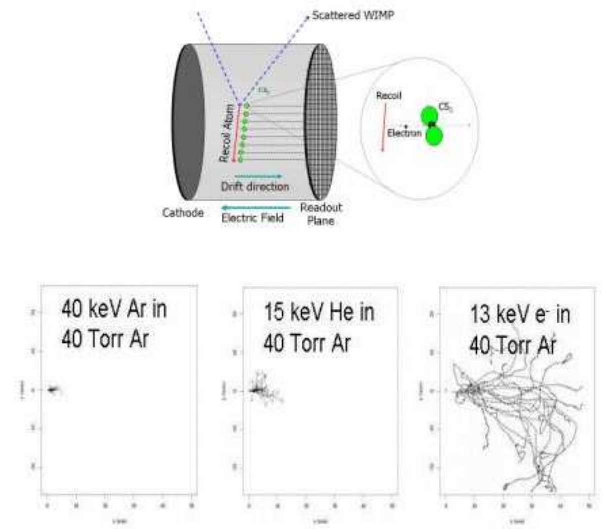

Figure 11. DRIFT-1 ionization tracks for three different types of recoiling particles : argon, helium and electrons.

first step will operate 21×320 g germanium detectors with NTD thermometers and 7×200 g NbSi thin film germanium detectors developed by the group of the CSNSM laboratory.[41] 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 to be two orders of magnitude below the present EDELWEISS-I sensitivity $\simeq$ 0.2 evt/kg/day. Such a background has to be clearly identified and rejected since the expected event rate for the EDELWEISS-II stage is about 10^{-2} evt/kg/day. In a second step, up to 120 detectors will operate simultaneously.

The CRESST-II[42] and ROSEBUD[43] experiments involve scintillating crystals as cryogenic detectors. They operate in the same way; the heat is measured with a thermometer glued on the scintillator and the light is collected with a second thin but large surface crystal. The main advantage of such a method is the large possibility for scintillating target materials: $CaWO_4$, $PbWO_4$, Al_2O_3, BaF, BGO, ... and for large volumes. A few years ago S. Pécourt *et al.*[44] characterized the phonon channel of a 1 kg Al_2O_3 bolometer and recently the same team[43] has succeeded in measuring the light output of a 50 g Al_2O_3 bolometer (Fig. 8).

The CRESST-II[42] experiment should operate 33×300 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 and near future experiments, other promising techniques are under investigation.

The PICASSO[45,46] and SIMPLE[47] 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}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 that the electron recoil induced by gamma background can be supressed. Calibration is made at different pressures and temperatures with mono-energetic neutrons produced by a Van de Graff Tandem. The use of ^{19}F (spin-1/2 isotope) makes the search for spin-dependent neutralinos particularly interesting. 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 environnement in the SNO underground laboratory: PIC@SNO. New purification techniques were developed especially for the PICASSO experiment.[48] 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 collaboration has developed and is currently running successfully, the DRIFT-I detector. It consists of a 1 m^3 low pressure TPC filled with a $Xe - CS_2$ gas mixture. The principle of the TPC is well known, the innovation is the use of CS_2 negative ions instead of 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 and hence the target mass, are underway. Other possible target gases are also being studied to prepare for the next generation DRIFT-II and -III detectors 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, most of which are in the final stages, aim to improve

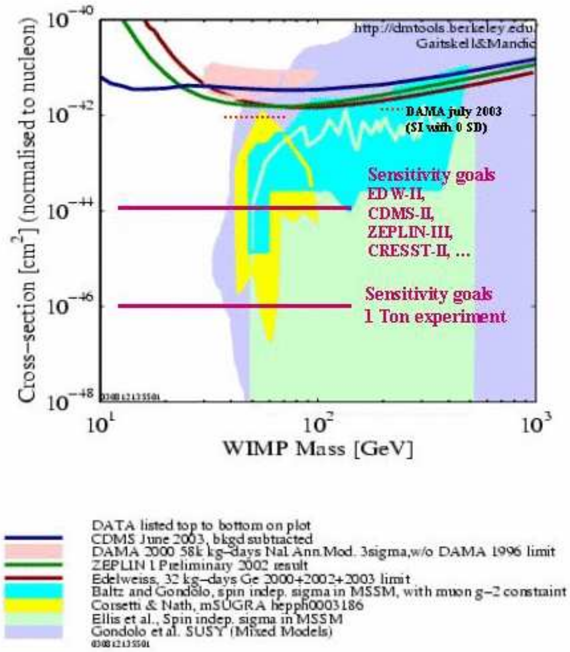

Figure 12. Projected limits for some of the next generation experiments. The colored regions represent different SUSY model calculations.

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 3×320 g Ge and EDELWEISS-II should run at the end with 120×320 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 ton 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 of mSUGRA models.

Acknowledgments

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DISCUSSION

Stan Wojcicki (Stanford University): Why has the DAMA allowed region on the WIMP mass versus cross section plane increased, and now allows for significantly smaller values of the cross section?

Maryvonne De Jésus: The DAMA allowed region on the WIMP mass versus cross section plane is increased because it is calculated with different values for some of the halo parameters, for example, a different WIMP velocity and a different local WIMP density.

Chang Kee Jung (SUNY at Stony Brook): Why is the dark matter halo in our galaxy assumed to be stationary against the motion of the rotating solar system? Namely, wouldn't a rotating dark matter halo be more natural? If so, how does this affect the experiments?

Maryvonne De Jésus: The dark matter halo in our galaxy is assumed to be stationary against the motion of the rotating solar system for convenience. This assumption is a simple model commonly used by experimentalist to compare data in the same WIMP mass versus cross section plane. But some authors, like A. Green, investigated other non-co-rotating halos and deduced that WIMP interaction rates strongly depend on the halo model.

Mike Albrow (Fermilab): The DAMA time variations are clearly not statistical fluctuations. Are there conventional explanations (excluding that it has seen dark matter) for it?

Maryvonne De Jésus: The Dama collaboration check all possible background origins which could give rise to an annual modulated signal similar to that observed. They declared everything is understood and the observed signal can't be mimicked by a background signal and hence the signal is produced by galactic WIMPS.

Bennie Ward (Baylor University & the University of Tennessee): The two events which you said could be interpreted as neutron-induced were, nonetheless, not so treated. Could you explain the corresponding logic of their treatment?

Maryvonne De Jésus: The two events observed by the EDELWEISS collaboration during the last campaign in June 2003 could be explained by some holes in the neutron shielding which appeared recently. This shielding is made of paraffin which is very sensitive to temperature variations. Other possible background origins are still under investigation.