Direct detection of WIMPs with conventional (non-cryogenic) detectors. Experimental review *

Angel Morales†
Laboratory of Nuclear and High Energy Physics and Canfranc Underground Laboratory (LSC)
University of Zaragoza
50009 Zaragoza. Spain

An overview of the current status of WIMP direct searches with conventional detectors is presented, emphasizing strategies, achievements and prospects.

1. Introduction

Experimental observations and robust theoretical arguments have established that our universe is essentially non-visible, the luminous matter scarcely accounting for one per cent of the energy density of a flat universe. The distribution of a flat universe \((\Omega = \Omega_M + \Omega_\Lambda = 1)\) attributes to the dark energy about \(\Omega_\Lambda \sim 70\%\), whereas the matter density takes the remaining \(\Omega_M \sim 30\%\), consisting of, both, visible \((\Omega_l \sim 0.5\%-1\%)\) and non-visible (dark) matter. This dark component is formed by ordinary baryonic matter \((\Omega_B \sim 4-5\%)\), (possibly made by MACHOs, jupiters, dust, black holes, etc.) and a large fraction (up to \(\Omega_{NB} \sim 25\%)\) of non baryonic dark matter, supposedly made by non-conventional, exotic particles.

These non-baryonic particles (usually named particle dark matter) would be filling the galactic halos, at least partially, according to a variety of models. It is supposed to be a suitable mixture (cold and hot dark matter) to properly generate the cosmic structures. The minimal requirements to be fulfilled by the non-baryonic dark particles are to provide the right relic abundance, to have non-zero mass, zero electric charge and very weak interaction with ordinary matter.

There are several candidates to such species of matter provided by schemes beyond the Standard Model of Particle Physics. Remarkable examples are the axions, WIMPs (Weak Interacting Massive PArticles) and neutrinos. Axions are pseudoscalar Nambu-Goldstone bosons arising from the spontaneous symmetry breaking of the Peccei-Quin \(U(1)_{PQ}\) symmetry invented to solve the strong CP problem. They are very weakly coupled to ordinary matter; examples are the galactic DM axions of the models KSUZ and DFSZ. Axions with large \(f_a(\sim 10^{12} GeV)\) are good candidates to dark matter, where \(f_a\) is the energy scale of the PQ symmetry breaking. The more favorable mass window for this candidate is \(10^{-5(-6)} eV < m_a < 10^{-(2-3)} eV\).

Another popular candidate are the weak interacting, neutral and massive particle, called WIMPs. A particularly attractive kind of WIMPs are provided by the SUSY models, like the neutralinos (the lightest stable particles -LSP-) of super symmetric theories. The lowest-mass neutralino is a linear superposition of photino, zino, higgsino, expressed as \(\chi \equiv a_1\tilde{\gamma} + a_2\tilde{z} + a_3\tilde{H}_1^0 + a_4\tilde{H}_2^0\) where \(P \equiv a_1^2 + a_2^2\) and \(P > 0.9\) gaugino; \(P < 0.1\) higgsino. The mass window of this candidate is \(GeV \leq m_\chi \leq TeV\). An interesting mass region, for reasons which will become clear later on, is that of \(40GeV \leq m_\chi \leq 200GeV\).

The last candidate is the (non-zero mass) neutrino of theories beyond the Standard Model. The neutrinos are the only candidate known to exist, have well-known weak interaction and only a small amount of them is needed to explain cosmic data. Their mass-window is very wide according to the particular model (to fit also other

---

*Invited Review Talk given at the XXX International Meeting on Fundamental Physics, IMFP2002, February 2002, Jaca, Spain.
†amorales@posta.unizar.es
phenomenology of $\nu$-physics). It is to be noticed that the masses of the non baryonic particle candidates extend along more than 18 orders of magnitude: $10^{-6}$ eV - $10^{15}$ eV. On the other hand, all the candidates have a common feature: their small interaction cross section with ordinary matter. In the case of WIMPs, for instance, various implementations of the Minimal SUSY extension of the Standard Model, MSSM, lead to an interaction cross-section $\sigma_{\chi,N}$, encompassing several orders of magnitude from $10^{-5}$ down to $10^{-10}$ pb. This cross-section plays a leading role in the estimation of the sensitivity required in particle dark matter searches.

This talk will be devoted only to one of these candidates: the WIMPs. Without entering into considerations about how large the baryonic dark component of the galactic halo could be, we take for granted that there is enough room for WIMPs in our halo to try to detect them, either directly or through their by-products. Discovering this form of Dark Matter is one of the big challenges in Cosmology, Astrophysics and Particle Physics.

WIMPs can be looked for either directly or indirectly through their byproducts. The indirect detection of WIMPs proceeds currently through two main experimental lines: either by looking in cosmic rays experiments for positrons, antiprotons, or other antinuclei produced by the WIMPs annihilation in the halo (like in the CAPRICE, BESS, AMS, GLAST, VERITAS, MAGIC experiments ...), or by searching in large underground detectors (SUPERKAMIOKANDE, SNO, SOUDAN, MACRO) or underwater neutrino telescopes (BAIKAL, AMANDA, ANTARESP, NESTOR) for upward-going muons produced by the energetic neutrinos emerging as final products of the WIMPs annihilation in celestial bodies (Sun, Earth...).

The direct detection of WIMPs relies in measuring the nuclear recoil produced by their elastic scattering off target nuclei in suitable detectors. The signal rate depends of the type of WIMP and interaction, whereas simple kinematics says that the energy delivered in the WIMP-nucleus interaction is very small. In the case of WIMPs of $m \sim GeV$ to $TeV$ and $v \sim 10^{-3}c$ the nuclear recoil energy in the laboratory frame $E_R = \frac{\mu^2 v^2 (1-\cos\theta)}{M}$ is in the range from 1 to 100 keV. $M$ is the nuclear mass, $\mu$ the $(m, M)$ reduced mass and $\theta$ the WIMP-nucleus (c. of m.) scattering angle. Even small the recoil energy, only a fraction $QE_R = E_{vis}(\equiv E_{ee})$ of it is visible in the detector, depending on the type of detector and target and on the mechanism of energy deposition. The so-called Quenching Factor Q is essentially unit in thermal detectors whereas for the nuclei used in conventional detectors it ranges from about 0.1 to 0.6. For instance for a Ge nucleus only about 1/4 of the recoil energy goes to ionization.

On the other hand, the smallness of the neutralino-matter interaction cross-section makes the rates of the nuclear recoil looked for very small. The variety of models and parameters used to describe the Astrophysics, Particle Physics and Nuclear Physics aspects of the process makes, as stated before, the neutralino-nucleus interaction rate encompass several orders of magnitude, going from 10 to $10^{-5}$ c/kg day, according to the SUSY model and parameters $[1]$. In fact, it is not higher than $10^{-2}$ c/kg day, for the neutralino parameters which provide the most favourable relic density.

The rare ($\leq 10^{-2}$ c/kg.day) and small (keV range) WIMP signal falls in the low energy region of the spectrum, where the radioactive and environmental background accumulate at much faster rate and with similar spectral shape. That makes WIMP signal and background practically undistinguishable. In conclusion, due to the properties of the expected signals, the direct search for particle dark matter through their scattering by nuclear targets requires ultralow background detectors of a very low energy threshold, endowed, when possible, with background discrimination mechanisms. All these features together make the WIMP detection a formidable experimental challenge.

This review will deal with the efforts currently being done in the direct search of WIMPs illustrated by a few experiments. Only conventional, non-cryogenic detectors, will be considered in this review (the case for cryogenics detectors will be addressed in the review of L. Mosca, in these Proceedings). The signals to be expected, their
main features, the techniques employed and the achievements accomplished will be overviewed. The current results and prospects will be also sketched.

2. Detecting WIMPs

The method to explore whether there exists or not a WIMP signal contribution in the experimental data is rather simple: one compares the predicted event rate with the observed spectrum; if the former turns out to be larger than the measured one, the particle which would produce such event rate can be ruled out as a Dark Matter candidate. That is expressed as a contour line $\sigma(m)$ in the plane of the WIMP-nucleon elastic scattering cross section versus the WIMP mass. For each mass $m$, those particles with a cross-section above the contour line $\sigma(m)$ are excluded as dark matter. The level of background sets, consequently, the sensitivity of the experiment to eliminate candidates or in constraining their masses and cross sections. Thus, the first effort to be done in looking for WIMPs must be on diminishing the general background and then in discriminating the background from the signal (nucleus recoil generated by WIMPs).

However, this mere comparison of the expected signal with the experimentally observed spectrum it is not expected, in principle, to lead to the WIMP’s detection, unless one reach a reliable zero-background ideal spectrum. In the general case, the real spectrum, even small, which has typically the same shape than that of the signal, could be due to pure background sources. After the identification and rejection of most of background sources, there still exists a worrisome background originated by the neutrons which produce also nuclear recoils similar to the produced by WIMPs.

This ultimate background must be identified and eliminated. However, a convincing proof of the detection of WIMPs would need to invent and discover signatures in the data characteristic of the WIMPs but not of the background. There exist temporal and spatial asymmetries specific of the WIMP interaction, which are difficult to be faked by the background or by instrumental artifacts. They are due to the kinematics of the motion of the Earth (and of our detectors) in the galactic halo. These signatures are an annual modulation of the rate and a directional asymmetry of the nuclear recoil (see later on). Both types of asymmetries are not characteristics of the background and, in principle, can be used as identification labels of the WIMPs. The only distinctive signature seriously investigated up to now is the annual modulation of the WIMP signal rate due to the seasonal variation produced by the Earth’s motion with respect to the Sun. Several experiments have looked for such seasonal variations of the rates and, in fact, the DAMA experiment, after four yearly period of data has found an annual modulation at the $3\sigma$ level, which has been associated, by the DAMA collaboration, to the existence of a WIMP.

From the experimentalist point of view, to detect WIMPs one need first to narrow the window ($\sigma,m$) of its possible existence, by means of the exclusion plots, and then try its identification through one, or more, of its distinctive features.

The detectors used so far in the quest for WIMPs (and references later on) are: ionization detectors of Ge (IGEX, COSME, H/M, HDMS) and of Si (UCSB), scintillation crystals of NaI (ZARAGOZA, DAMA, UKDMC, SACLAY, ELEGANTS), liquid or liquid-gas Xenon detectors (DAMA, UCLA, UKDMC, ZEPLIN), calcium fluoride scintillators (MILAN, OSAKA, ROMA), thermal detectors (bolometers) with sapphire absorbers (CRESST, ROSEBUD), with tellurite absorbers, (MIBETA, CUORICINO) or with germanium absorbers (ROSEBUD) as well as bolometers which also measure the ionization, like that of Si (CDMS) and of Ge (CDMS, EDELWEISS). New techniques have been recently incorporated. Worth to be mentioned are: scintillating bolometers of calcium tungstate which measure heat and high (CRESST and ROSEBUD), and of BGO (ROSEBUD); a TPC sensitive to the direction of the nuclear recoil (DRIFT); devices which use superheated droplets (SIMPLE and PICASSO), or those which use colloids of superconducting superheated grains (ORPHEUS).

There exist also projects featuring a large
amount of target nuclei in segmented detectors, both with ionization Ge detectors (GENIUS, GEDEON) and cryogenic thermal devices (CUORE). Table 1 gives a rough account of the “history” of WIMP searches. Table 2 gives an overview of the experiments on direct detection of WIMPs currently in operation or in preparation. General reviews on WIMPs can be found in Ref. [2] whereas neutralino dark matter has been extensively described in Ref. [1] (see also the A. Bottino talk in these Proceedings). WIMP direct detection are reviewed, for instance in Ref. [3].

3. Strategies for WIMP direct detection

Noticed first that the smallness of the predicted rate (which goes from $R \sim 1 - 10 \text{ c/kg.day}$ down to $10^{-4} - 10^{-5} \text{ c/kg.day}$) implies that the sensitivity of the experiment must be driven to the best possible achievable value in this range. The $\sigma_{\chi N}$ calculations are made within the Minimal Supersymmetric extension of the Standard Model, MSSM, as basic frame, implemented in various schemes (see Ref. [1]). Besides the peculiarities of the SUSY model there is a wide choice of parameters entering in the calculation of the rates: the halo model, the values of the parameters in the WIMP velocity distribution, the three levels of the WIMP-nucleus interaction (quark-nucleon-nucleus) and the constraint of getting the proper relic abundance of the candidates, just to mention a few.

From all these ingredients it follows that the theoretical prediction of the rates show considerable spreading and are presented as “scatter plots” extending along the various orders of magnitude quoted above. Some of the most favorable predictions are already testable by the leading experiments which have, in fact, penetrate into the scatter plot of predictions. The bottom of the plot is still far away of the detector sensitivity. It should be noted, however, that most of the experimental searches for SUSY-WIMPs concentrate in the dominant, coherent interaction, which provides the largest signals but our scarce knowledge of the nature of the WIMP interaction makes other options non-negligible.

The rarity and smallness of the signals dictate the obvious strategy: to use ultra-low background detectors of the lowest possible energy threshold plus one (or various) unambiguous background rejection mechanisms, all these prescriptions carried out in a radioactivity-free environment (including shielding, experimental devices, ...). Example of low background recently achieved is the case of IGEX, with Ge ionization detectors; the cases of the CDMS and EDELWEISS which use Ge thermal detectors which also measure ionization to discriminate, and that of ZEPLIN which uses background discrimination in liquid Xenon.

Examples of low energy threshold and high efficiency detectors are the bolometer experiments (MIBETA, CRESST, ROSEBUD, CUORICINO, CDMS and EDELWEISS) which seen efficiently the energy delivered by the WIMP (quenching factor essentially unity) and which have achieved very low energy thresholds ($E_{THR} \sim $ hundreds of eV).

To search for such rare events large masses of targets are also recommended, to increase the probability of detection and the statistics. The DAMA, UKDMC and Zaragoza scintillations experiments use from 50 to 100 kg of NaI; the CUORICINO bolometer experiment is installing 39.5 kg of TeO$_2$ crystals and the ZEPLIN detector which uses (according to the various versions) 20 to 40 kg of Xe. It is remarkable that small size, first generation detectors have reached exclusions $\sigma_{\chi p} > 10^{-5} - 10^{-6} \text{ pb} (10^{-41} - 10^{-42} \text{ cm}^2)$ in the range of masses relevant for SUSY-WIMPs.

The basic idea behind the background rejection techniques is to discriminate first electron recoils (tracers of the background) from nuclear recoils (originated by WIMPs and neutrons). Methods used to discriminate backgrounds from nuclear recoils are either simply statistical, like a pulse shape analysis, PSD (based on the different timing behavior of both types of pulses), or on an event by event basis by measuring simultaneously two different mechanisms of energy deposition having different responses for background and signals, like the ionization (or scintillation) and the heat produced by the WIMP-induced nuclear recoil, and capitalizing the fact that for a given deposited energy (measured as phonons) the recoiling nucleus ionizes less than the electrons. Exam-
Table 1
WIMP direct searches history

| Year | Ge IONIZATION DETECTORS | SCINTILLATORS |
|------|-------------------------|---------------|
| 1986 | USC-PNNL (Homestake)    | ZARAGOZA NaI (Canfranc) |
|      | UCSB-LBL (Oroville)     | ROMA lqXe (Gran Sasso)  |
|      | ZAR-USC-PNL (Canfranc)  | ROMA/SACLAY NaI (LSM/LNGS) |
|      | CALTECH-PSI-N (Gothard) | UKDMC NaI (Boulby)     |
| 1990 | H/M (Gran Sasso)        | DAMA NaI, CaF$_2$ (LNGS) |
|      | IGEX (Canfranc)         | SACLAY NaI (Frejus)    |
|      | COSME (Canfranc)        | ELEGANTS NaI, CaF$_2$ (Oto) |
|      | TAN-USC-PNL-ZAR (Sierra G) | ZEPLIN Xe (Boulby) |
|      | IGEX (Baksan)           | NAIAD NaI (Boulby)     |
|      | HDMS (Gran Sasso)       | 2000 ANAIS NaI (Canfranc) |
| 2002 | GENIUS-TF (Gran Sasso)  | 2002 LIBRA NaI (LNGS)  |

| Year | THERMAL DETECTORS (PHONONS) | CRYO-DET (PHON+IONIZ) |
|------|-----------------------------|-----------------------|
| 1988 | MIBETA TeO$_2$ (LNGS)       | 1988 CDMS-I Si/Ge (SUF) |
|      | EDELWEISS-0 Al$_2$O$_3$ (Frejus) | 90’s EDELWEISS I Ge (Frejus) |
| 90’s | CRESS-I Al$_2$O$_3$ (LNGS)  | 2001 EDELWEISS II (Frejus) |
|      | ROSEBUD Al$_2$O$_3$/Ge (Canfranc) | 2002 CDMS-II Ge/Si (Soudan) |
| 2002 | CUORICINO TeO$_2$ (LNGS)    |                       |
| 2005 | CUORE TeO$_2$ (LNGS)        |                       |

| Year | CRYO-DET (PHONONS+LIGHT) | SUPER. SUPERHEATED DET. |
|------|--------------------------|-------------------------|
| 2000 | CRESS-II CaWO$_4$ (LNGS) | R+D of SSD since 80’s   |
| 2001 | ROSEBUD CaWO$_4$ and BGO (Canfranc) | Paris, Munich, Garching, Bern, Zaragoza, Oxford, Lisbon |
|      |                           | 2001 ORPHEUS Sn (Bern UF) |

| Year | TPC | SUPERH. DROPLET DET. SDD |
|------|-----|--------------------------|
| 2002 | DRIFT Xe (Boulby) | 1997 SIMPLE Freon (Rustrel) |
| 2005 |                 | 1997 PICASSO Freon (SNO)   |

Examples of PSD are the sodium iodide experiments of UKDMC, Saclay, DAMA and ANAIS. Notable discrimination is also obtained in liquid scintillators like the ZEPLIN detectors. Event by event discrimination has been successfully applied, for instance, in CDMS and EDELWEISS by measuring ionization and heat and in CRESST and ROSEBUD by measuring light and heat.

Another discriminating technique is that used in the two-phase liquid-gas Xenon detector with ionization plus scintillation, of the ZEPLIN series of detectors. An electric field prevents recombination, the charge being drifted to create a second pulse in addition to the primary pulse. The amplitudes of both pulses are different for nuclear recoils and electrons and that allows their discrimination.

One could use instead threshold detectors–like neutron dosimeters– which are blind to most of the low Linear Energy Transfer (LET) radiation ($e$, $\mu$, $\gamma$) and so able to discriminate gamma background from neutrons (and so WIMPs). Detectors which use superheated droplets which vaporize into bubbles by the WIMP (or other high LET particles) energy deposition are those of the SIMPLE and PICASSO experiments. An ultimate discrimination will be the identification of the different kind of particles by the tracking they left in, say, a TPC, plus the identification of the WIMP through the directional sensitivity.
of the device (DRIFT). Intense R+D programs are underway to use devices with such kind of sensitivity. Tables 3 to 5 gives, synoptically the main non-cryogenic experiments currently running, summarizing some of their features. Section 5 to 9 will describe and comment the results of some of these experiments.

4. Excluding WIMPs of the DM budget

The direct experiments measure the differential event rate (energy spectrum) in the customary differential rate unit (dru) $\frac{dR}{dE_{vis}}$ (c/keVkgday). The registered counts contain the signal and the background. Then, by applying discrimination techniques one disentangles at least partially the nuclear recoils from the background events. The resulting residual rate is then compared (in terms of $m$, and $\sigma_{\chi N}$) with the theoretical nuclear recoil rate due to WIMPs interaction first derived by Goodman and Witten [4].

The differential rate is expressed as

$$\frac{dR}{dE} = N \frac{\rho}{m} \int_{V_{min}}^{V_{esc}} \frac{d\sigma(v,E_R)}{dE} \bar{v} f(\bar{v})d^3v$$

where $f(\bar{v})$ is the velocity distribution of WIMPs in the laboratory frame and $d\sigma/dE_R$ the differential cross-section WIMP-nucleus. By assuming dominance of coherent cross-section one has

$$\frac{dR}{dE} = N \frac{\rho}{m} \frac{(m + M)^2}{2m^2 M} \sigma_{\chi N}^{SI} F^2(q) I(E)$$
where $F$ is the nuclear form factor and $I$ the integral $I \equiv \int_{v_{\text{min}}}^{v_{\text{esc}}} \frac{f(v)}{v} dv$, $\sigma_{\chi N}^{SI}$ is the cross-section WIMP-nucleus of the detector and is usually parameterized in terms of the WIMP-nucleon cross-section. For the standard halo model (isothermal sphere), currently used as a first approximation to the galactic halo, the velocity distribution function reads,

$$f(v) dv = \left(\frac{\sqrt{3/2\pi}}{v_{\text{rms}}^3}\right)^3 \exp \left\{-\frac{3(v + \bar{v}_E)^2}{2v_{\text{rms}}^2}\right\} dv$$

with $v_{\text{rms}} \sim \sqrt{3/2} v_{\text{Sun}}$

$$\left[\frac{dR}{dE_{\text{VIS}}}\right]_{\text{Th}} = 7.76 \times 10^{14} \frac{N}{Q v_E} \frac{\rho (m + M)^2}{4\pi M^2} F^2 \sigma_{\chi N}^{SI} \tau$$

(with $\sigma$ in $\text{cm}^2$, $m$ and $M$ in GeVs, $v$ in $Km s^{-1}$, $\rho$ in $GeV cm^{-3}$ and $N$ in $kg^{-1}$) where $\rho$ is the local density of WIMP, $N$ the number of target nuclei, $F^2$ is the nuclear form factor, and $\tau(v_{\text{esc}} \to \infty) = erf(x + y) - erf(x - y)$, with

$$x, y = \sqrt{\frac{3}{2}} (v_{\text{min}}, v_E) \frac{1}{v_{\text{rms}}} , \quad v_{\text{rms}} \sim \sqrt{\frac{3}{2}} v_{\text{Sun}}$$

$v$ the WIMP velocity (Earth/Lab frame) and $v_E$ the velocity of Earth/Solar system with respect to the halo.

$v_{\text{min}}(E_R) = \frac{m + M}{m} (E_R/2m)^{1/2}$ is the minimal velocity to produce a recoil $E_R$. The spin-independent nuclear cross-section is usually normalized in terms of that on nucleons

$$\sigma_{\chi N}^{SI} = \frac{\sqrt{\pi}}{\sqrt{2\pi}} \sigma_{\text{scalar}}^{\text{nucleon(p,n)}}$$

Those values of $(\sigma, m)$ predicting a recoil spectrum above the observed rate

$$\left[\frac{dR}{dE_{\text{VIS}}}\right]_{\text{Th}} \geq \left[\frac{dR}{dE_{\text{VIS}}}\right]_{\text{Exp}}$$

are excluded. The region above the contour $\sigma(m)$ is depicted as an exclusion plot of those WIMPs of mass $m$ with interaction cross-section above $\sigma$. Obviously, the smaller the background the better the exclusion.

### 5. The identification of WIMP dark matter

After reducing maximally the background and extremating the discrimination (99.99%) of the detector, one should look for asymmetries characteristic of WIMP signals. Typical smoking guns of WIMPs could be the annual modulation of the rate $[6]$, the forward/backward asymmetry of the nuclear recoil $[7]$ or the nuclear target dependence of the rates $[8]$.

The two kinematical asymmetries characteristic of WIMPs signals are originated by the Earth motion through the galactic halo. The Earth orbital motion around the Sun has a summer/winter variation, which produces a small annual modulation of the WIMP interaction rates, of the order $O (\frac{v_{\text{Sun}}}{v_E}) \sim \frac{15}{\sqrt{76}} \sim 5\%$. The observation of a tiny modulation of a very small signal requires large target mass and exposure, superb stability and extreme control of systematic and of other stational effects.

The orbital velocity of Earth around the sun is of $30 Kms^{-1}$ in an orbit inclined $\alpha = 60^\circ$ with respect to the galactic disk

$$v_{E,R} = 30 \cos \alpha \cos \omega(t-t_0) \to 15 \cos \omega(t-t_0) Kms^{-1}$$

$$\omega = \frac{2\pi}{T} \quad T = 1\text{year} \quad t_0 : \text{June 2\text{nd}}$$

So, the velocity of the Earth (and of our earth-born detector) relative to the galactic halo is

$$v_E = v_{\text{Sun}} + 15 \cos \omega(t-t_0) Kms^{-1}$$

Consequently, in summer there is a component of the Earth’ motion around the sun parallel to the sun motion through the galaxy which adds 15 $Kms^{-1}$. On the contrary, in winter the same occurs but the motion is antiparallel and so one has to subtract 15 $Kms^{-1}$. The result is that the detector moves slightly faster in June than in December (5% effect), and consequently a modulation of the WIMP interaction rates follows, given at first order by

$$S(t) = S_0 + S_m \cos \omega(t-t_0) + B$$

where $S_0$ is the average signal amplitude, $S_m$ the modulated amplitude and $B$ the constant background.
The annual modulation signature has been already explored. Pioneering searches for WIMP annual modulation signals were carried out in Canfranc (NaI-32)[8], Kamioka (ELEGANTS)[9] and Gran Sasso (DAMA-Xe)[10]. In July 1977 the DAMA experiment at Gran Sasso, using a set of NaI scintillators, reported an annual modulation effect which after four yearly periods[28] has a 3σ level significance. Such effect is compatible with the seasonal modulation rate which could be generated by a WIMP and so, it has been attributed by the DAMA collaboration to a WIMP of about 60 GeV of mass and of scalar cross-section on protons of $\sigma_p = 7 \times 10^{-6}$ pico-barns.

A second characteristic signature of the WIMP is provided by the directional asymmetry of the recoiling nucleus [6]. The WIMPs velocity distribution in the Earth frame is peaked in the opposite direction of the Earth/Sun motion through the halo, and so the distribution of nuclear recoils direction shows a large asymmetry forward/backward (F/B) not easily mimicked by the supposedly isotropic background. The order of magnitude of the effect is large because the solar system’ motion around the galactic center $v_{\text{sun}}$, and the typical WIMP velocity in the halo, $v_h$, are of the same order $O \left( \frac{v_{\text{sun}}}{v_h} \right) \sim \frac{230}{270} \sim 1$.

The angular dependence of event rate is given by (see Ref.[6])

$$\frac{d^2R}{dE_{\text{rec}}d(\cos \gamma)} = \frac{N\rho\sigma (m+M)^2}{\sqrt{\pi} 2m^3Mv_{\text{halo}}} \exp \left\{ \frac{(v_E \cos \gamma - v_{\text{min}})^2}{v_h^2} \right\}$$

where $\gamma$ is the angle of the recoiling nucleus.

There exists an increasing interest in developing devices sensitive to the directionality of nuclear recoils from WIMPs and, in general, to the tracking of particles. Chambers with such purpose are being used or planned for experiments in rare event physics. The DRIFT (Direction Recoil Identification From Tracks) detector is a TPC of Xe (or other gases), which is sensitive to the directionality of the nuclear recoil. The forward-backward asymmetry of the WIMP signal will be investigated with that device. Information and current results of the experiments mentioned above can be found in [8] and References therein and in the Proceedings of the series of TAUP Conferences[11]. See also the Proceedings of the Neutrino 2002 Conference.

Recently, the nuclear recoil angular dependence of WIMP interactions has been analyzed in different halo models with the purpose of exploring how well a directional signal can be distinguished without ambiguity from the background -with independence of the halo model-. Quite remarkably, if the device has angular resolution sensitivity, few events will be enough to distinguish the signal, and not too many are needed if it has only F/B sensitivity (see Ref.[12]).

Another asymmetry is the nuclear target dependence of the rate [6], for instance in the nuclear mass $A$, or in the nuclear spin $J$. However, due to the differences in the intrinsic backgrounds of the various targets, it is not easy to get reliable conclusions. Some experiments are operating (or could it) sets of similarly produced crystals of different nuclear targets in the same environment like ROSEBUD (Ge/Al$_2$O$_3$/CaWO$_4$)[13] with the objective of exploring such nuclear target dependence.

6. Germanium Experiments

The high radiopurity and low background achieved in Germanium detectors, their fair low energy threshold, their reasonable Quenching Factor (about 25%) (nuclear recoil ionization efficiency relative to that of electrons of the same kinetic energy, or ionization yield) and other nuclear merits make Germanium a good option to search for WIMPs with detectors and techniques fully mastered. The first detectors applied to WIMP direct searches (as early as in 1987) were, in fact, Ge diodes[14,15,16,17,18,19,20], as by-products of 2$\beta$-decay dedicated experiments. Table 3 shows the Germanium ionization detector experiments currently in operation. We will review however only some examples. Pioneer germanium experiments looking for WIMPs are described in Refs.

The International Germanium Experiment
Table 3
Ge Ionization Experiments

| Experiment and site  | M (kg)  | $E_{T_{th}}$(keV) | $\Gamma$(keV) | Low Energy B(c/keVkgday) | Observations                              |
|----------------------|---------|-------------------|--------------|--------------------------|-------------------------------------------|
| COSME-II LSC-Canfranc| 0.234   | 2.5               | 0.4 (at 10 keV) | 0.6(2-15 keV)            | Good exclusions for low mass WIMPs        |
| LSC-Canfranc         | (311d)  |                   |              | 0.3(15-30 keV)           |                                           |
| IGEX                 | 2.1     | 4                 | 2 (at 10 keV) | 0.21 (4-10 keV)          | 1 detector from IGEX enriched 76Ge set (2β) |
| LSC-Canfranc         | (139d)  |                   |              | 0.10 (10-20 keV)         |                                           |
|                      |         |                   |              | 0.04 (20-40 keV)         |                                           |
| H/M LNGS             | 2.76    | 9                 | 2.4 (at 727 keV) | 0.16 (9-15 keV)         | 1 detector from H/M enriched 76Ge set (2β) |
| (250d)               |         |                   | extr. 2 at 0 keV | 0.042 (15-40 keV)       |                                           |
| HDMS LNGS            | inn. 0.2| 2.5               | 1.2 (at 300 keV) | 0.2 (11-40 keV)         | Small detector inside a well-type Ge       |
|                      | out. 2.1| 7.5               | 3.2 (at 300 keV) | 0.07 (40-100 keV)       | outer crystal                             |
|                      | (49d)   |                   | extr. 3 at 0 keV |                         |                                           |
| GENIUS-TF LNGS       | 40      | 0.5 nom.          |              | goal                     | 14 Ge crystals embedded in liquid nitrogen|
| In preparation       | (2.7x14)| 12 eff.           |              | $10^{-2}$                | housed in zone-refined Ge bricks          |
| GENIUS Project       | 100-    | > 12              |              | goal                     | Large set of naked p-type Ge detectors    |
| Project              | 100000  | (cosmog.)         |              | $10^{-4} - 10^{-5}$      | in liquid Nitrogen                         |
| GEDEON Project       | 56      | 1-2 nom.          | 1 (at 10 keV) | goal                     | 28 Ge diodes in one single cryostat       |
| LSC-Canfranc         | 4x7(2kg)| 12 eff.           |              | $10^{-2} - 10^{-3}$      | archaeological lead and pure graphite     |
|                      | (cosmog.)|                  |              | (2-50 keV)               |                                           |

(IGEX) which was optimized to search for the double beta decay of germanium $^{76}$Ge is using one enriched detector of $^{76}$Ge of $\sim 2.1$ Kg to look for WIMPs in the Canfranc Underground Laboratory [23,24]. It has an energy threshold of 4 keV and an energy resolution of 0.8 keV at the 75 keV Pb x-ray line. The detector is fitted in a cubic block in lead being surrounded by not less than 40-45 cm of lead of which the innermost 25 cm are archaeological. A muon veto and a neutron shielding of 40 cm of polyethylene and borated water completed the set-up [24]. The spectrum of IGEX-2000 [25] together with that of a previous run [24] (IGEX-2000) are shown in Fig. 1 in comparison with that of the Heidelberg-Moscow experiment [26]. The H/M experiment is another enriched-Ge experiment (enriched $^{76}$Ge crystal of 2.7 kg and energy threshold of 9 keV), already completed, which has been running at Gran Sasso.

The exclusion plots resulting from the IGEX data are derived from the recorded spectrum Fig. 1 in one-keV bins from 4 keV to 50 keV. The method followed in deriving the plot has been the same for all the detectors and experiments from which exclusion plots are depicted in this review. As recommended by the Particle Data Group, the predicted signal in an energy bin is required to be less than or equal to the (90% C.L.) upper limit of the (Poisson) recorded counts. The derivation of the interaction rate signal supposes that the WIMPs form an isotropic, isothermal, non-rotating halo of density $\rho = 0.3$ GeV/cm$^3$, have a Maxwellian velocity distribution with $v_{rms} = 270$ km/s (with an upper cut corresponding to an escape velocity of 650 km/s), and have a relative Earth-halo velocity of $v_r = 230$ km/s. The cross sections are normalized to the nucleon, as-
assuming a dominant scalar interaction. The Helm parametrization [27] is used for the scalar nucleon form factor, and the recoil energy dependent ionization yield used is the same that in Ref. [26].

\[ E_{\text{vis}} = 0.14(E_{\text{REC}})^{1.19} \]

The best exclusion plot derived for these Ge experiments, that of IGEX-2001, is depicted in Fig. 2 and labelled on the right border of the figure. IGEX-2001 improves the exclusion of the other Ge-ionization experiments for a mass range from 20 GeV up to 200 GeV, which encompass the DAMA mass region [28]. In particular, IGEX excludes WIMP-nucleon cross-sections above \( 7 \times 10^{-6} \) pb for masses of 40-60 GeV and enters the DAMA region excluding the upper left part of this region. That is the first time that a direct search experiment with a Ge-diode without background discrimination, but with very low (raw) background, enters such region. A further 50 % background reduction between 4 keV and 10 keV would allow IGEX to explore practically all the DAMA region in 1 kg.y of exposure.

In Figure 2 we plot the exclusions that would be obtained by IGEX with a flat background rate of 0.1 c/keVkgday (dot-dashed line) and of 0.04 c/kgkeVday (solid line) down to the current 4 keV threshold, for an exposure of 1 kg.year [29].

\[ r^2 \text{ (nb/m)} \]

In Figure 3, IGEX-DM projections are shown for a flat background rate of 0.1 c/keVkgday (dot-dashed line) and 0.04 c/kgkeVday (solid line) down to the threshold at 4 keV, for 1 kg.year of exposure. The exclusion contour expected for GEDEON is also shown (dashed line) as explained in the text.

In Figure 3, also shown for comparison are the contour lines of the experiments which have crossed partially of totally the DAMA region like...
CDMS [30], EDELWEISS [31] and ZEPLIN [32]. The DAMA region (closed line) corresponding to the annual modulation effect reported by that experiment [28] and the exclusion plot obtained by DAMA NaI-0 [33] using statistical pulse shape discrimination are also shown.

There exist new experimental projects to look for WIMPs with Ge detectors: GEDEON (GErmanium DEtectors in ONe cryostat), is planned to use 56 kg of Ge of natural isotopic abundance [21,29,34]. It will use the technology developed for the IGEX experiment and it would consist of a set of ~2 kg Germanium crystals, of a total mass of about 56 kg, placed together in a compact structure inside one only cryostat. This approach could benefit from anticoincidences between crystals and a lower components/detector mass ratio to further reduce the background with respect to IGEX.

The GEDEON single cell is a cylindrical cryostat in electroformed copper hosting 28 germanium crystals which share the same common copper cryostat (0.5 mm thick). The Ge crystals, are arranged in four plates of seven detector each suspended from copper rods. The cell is embedded into a precision-machined hole made in a Roman lead block providing a shield of 20 cm, and surrounded by another lead shielding 20 cm thick. A cosmic veto and a large neutron shield complete the shielding.

The preliminary MC estimated intrinsic (assumed dominant) background in the 1~50 keV region ranges from $2 \times 10^{-2}$ to $2 \times 10^{-3}$ c/keV.kg.day, according to the level of radioimpurities included as input [35]. The radiopurity assays have been carried out in the Canfranc Laboratory for the lead and copper components of the shielding. The background final goal of GEDEON, below 100 keV, would be in the region of $10^{-3}$ c/keV.kg.day and this value has been used to calculate anticipated $\sigma(m)$ exclusion plots in the most favourable case. The expected threshold assumed has been $E_{\text{thr}} = 2$ keV and the energy resolution in the low energy region has been taken $\Gamma \sim 1$ keV. The MC estimated intrinsic background of the GEDEON unit cell (28 crystals) is given in Fig. 4. A detailed study is in progress to assess the physics potential of this device. The exclusion plot which could be expected with such proviso in a first step (28 kg.y of exposure) is shown in Figure 3. Moreover, following the annual modulation sensitivity plots presented in [36], GEDEON would be massive enough to search for the WIMP annual modulation effect and explore positively an important part of the WIMP parameter space.

![Figure 4. Montecarlo estimated background of the GEDEON detector project (energy interval 0—50 keV).](image)

Two more Ge experiments running or in preparation, both in Gran Sasso, are that of the Heidelberg Dark Matter Search (HDMX) and the GENIUS-Test Facility. The small detector of HDMS has achieved a background still higher than that of H/M and so the results will not be included here. See Ref. [38]. Most of the attention of this Collaboration goes now to the preparation of a small version with natural abundance germanium detectors (GENIUS-Test Facility) of the GENIUS project [39]. GENIUS is a multipurpose detector, consisting of enriched Ge detectors of about $2^{1/2}$ kg each (up to a total of 0.1 to 10 tons) which uses the novel idea of immerse the crystals directly into a large tank of liquid nitrogen. GENIUS-TF, now in preparation, is intended to test the GENIUS project and at the same time to
search for WIMP.

7. WIMP searches with NaI scintillators

The sodium iodide detectors are very attractive devices to look for WIMP. Both nuclei have non-zero spin (\( ^{23}Na \ J = \frac{3}{2} \), \( ^{127}I \ J = \frac{5}{2} \)) and then sensitive also to spin dependent interaction. Iodine is a heavy nucleus favourable for spin-independent interactions. The quenching factor is small (\( Q < 10\% \)) for I, and medium for Na (\( Q \sim 30 - 40\% \)). Backgrounds lesser than or of the order of \( \sim 1 \ c/\text{keV kg day} \) in the few keV region have been achieved. There exists four NaI experiments running: DAMA, UKDMC, (in various detectors and projects), ELEGANTS and ANAIS, and other in preparation. Table 4 shows the main features of the current NaI experiments.

The NaI scintillators can be endowed with Pulse Shape Discrimination (PSD) to distinguish statistically gamma background from WIMPs (or neutron) signals, because of the different timing behavior of their pulses. From such statistical analysis it results that only a few percent (depending on the energy) of the measured background can be due to nuclear recoils. The background spectra (before PSD) of four NaI experiments ANAIS [1], DAMA [28], UKDMC [41] and Saclay [42] are shown comparatively in Fig. 5 (1 to 2 c/keV kg day in DAMA, UKDMC and ANAIS and of 2 to 10 c/keV kg day in Saclay and ELEGANTS [43]). Table 5 shows the typical background reduction obtained with PSD.

The United Kingdom Dark Matter Collaboration (UKDMC) uses radiopure NaI crystals of various masses (2 to 10 kg) in various shielding conditions (water, lead, copper) in Boulby [41]. Typical thresholds of 4 keV have been obtained. UKDMC is also preparing, NAIAD (NaI Advanced Detector) which will consist of 50–100 kg in a set of crystals. The exclusion plots obtained with these detectors (for spin independent couplings) are still worse than that of Ge and will not be included here.

ANAIS (Annual Modulation with NaI’s [44]) will use 107 kg of NaI(Tl) in Canfranc. A prototype of one single crystal (10.7 kg) is being developed. The components of the photomultiplier have been selected for its radiopurity. Pulse shape analysis has been performed. The preliminary results refer to an exposure of 2069.85 kg day (Fig. 6) shows the background after the noise rejection. The energy threshold is of \( \sim 4 \text{ keV} \) and the background level registered from threshold up to 10 keV is about 1.2 c/keV kg day.

The DAMA experiment [28] uses 9 radiopure NaI crystals of 9.7 kg each, viewed by two PMT. The software energy threshold is at \( E_{thr} = 2 \text{ keV} \) and the energy resolution at 2-5 keV is \( \Gamma \sim 2 - 2.5 \text{ keV} \). The PSD method applied to the DAMA NaI-0 [33] running lead to a background reduction of 85% (at 4–6 keV) and 97% (at 12–20 keV), providing remarkable exclusion plots.

The main objective of DAMA however is to search for the annual modulation of the WIMPs signal. Such modulation has been found and attributed by the Collaboration to a WIMP signal. After 57986 kg day of statistics the residuals of the rate vs time, looks as shown in Fig. 6. It modulates according to \( A \cos(\omega(t - t_0)) \) with period and phase consistent with 1 year and 2nd June, respectively. The probability of absence of modulation is \( \sim 4 \times 10^{-4} \). The DAMA global results [28] (NaI, 1, 2, 3, 4 running) in the case of assuming the WIMP interpretation, lead to a WIMP of mass and cross-section given by \( M_W = (52^{+10}_{-8}) \text{ GeV} \) \( \xi \sigma^p = (7.2^{+0.4}_{-0.3}) \times 10^{-6} \text{ pb} \).
### Table 4
**NaI Scintillation Experiments**

| Experiment and site | M (kg) | $E_{Th}$ (keV) | B(keV/kg/day) aver. after PSD | Observations |
|---------------------|--------|---------------|-------------------------------|--------------|
| UKDMC               | 2-10   | 4             | 2-4 (DM4G, 5 kg)              | Anomalous fast event found |
| Boulby              | 1.7 p.e./keV |   |                               | not yet fully understood |
| DAMA                | 9 x 9.70 | 2       | 1 ∼ 1.5 (at 2-3 keV)          | Annual modulation effect reported along four annual cycles (4σ). (5th and 6th cycles soon) |
| LNGS                | 7 p.e./keV | 2       | 1.5 ∼ 2 (at 3-6 keV)          | Phys. Lett. B450 (99)448; ibid B480 (2000) 23 |
| ELEGANT             | 730    | 4-5         | 8-10 (at threshold)           | Old set-up upgraded |
| Oto Cosmo           | 20 Modules | 4-5     |                               | Large BKG from $^{210}$Pb (10 mBq/kg) |
|                     |         |             |                               | Analysis only of 9 modules (328.5 kg) |
| ANAIS               | prototype | 2       | 3-4 (at 2 keV)               | 107 kg intended for ann. mod. search. |
| LSC-Canfranc        | 10.7   | 2          | 2 (at 3-5 keV)               | Old set upgraded plus new radiopure crystals |
| (Prototype running) | 10x10.7 | 1        | 1 (at 5-8 keV)               | Preliminary 1200 kg day |
|                     |         |           |                               | Also R+D in NaI unencapsulated |
| NAIAD               | units of 5-10 | 2       | 2 (2-20 keV) | Set of NaI unencapsulated |
| Boulby              | for a set of 40-50 | | expected | prototype: 5cmφ x5cm Crystal in polypropylene barrel 6-12 p.e./keV |
|                     |         |           |                               | No fast events seen |
| LIBRA (DAMA)        | 250    |             | R+D on detector radiopurity crystals | from ultrapure powders |
| LNGS                |         |           |                               | (In preparation) |

A maximum likelihood favours the hypothesis of presence of modulation with the above $M_W$, $\xi \sigma_p$ values at 4σ C.L. The ($\sigma$, m) region for spin independent coupled WIMP is the “triangle” zone depicted in Fig. 2. An extension of DAMA up to 250 kg of NaI (LIBRA) is being prepared.

The DAMA results have aroused great interest and controversies. It is imperative to confirm the DAMA results by other independent experiments with NaI (like LIBRA and ANAIS) and with other nuclear targets, say Ge and Te. For instance, CUORICINO[44,45], with 39.6 kg of TeO$_2$, is now being mounted. GEDEON and GENIUS–TF of about 56 and 40 kg of germanium respectively will critically explore that modulation (see Ref [36]). The DAMA $\sigma$(m) region is being explored, also by the standard method followed for excluding WIMPs. Various experiments have already reached and even trespassed the DAMA region (see in the Fig 2 the comprehensive exclusion plot including IGEX, CDMS, EDELWEISS and ZEPLIN).

The OSAKA group is performing a search with the ELEGANTS V NaI detector in the underground facility of Oto. ELEGANTS uses huge mass of NaI scintillators (760 kg) upgraded from a previous experiment. The background at threshold is still high. A search for annual modu-

---

![Figure 6](image-url)
Table 5
Examples of PSD background rejection in NaI experiments

| Experiment and site | Exposure | Method | PSD Background rejection 90%CL (Energy interval in keV) | Obs. |
|---------------------|----------|--------|-----------------------------------------------------|------|
|                     |          |        | 4-6       | 6-8 | 8-10 | 10-12 | 12-20 |                  |
| UKDMC               | 1122 kg.day time decay | const. | 85% | 92% | 94% | 96% | 97% | Phys Lett B779(96)299 |
| Boulby              | 181d x 6.2kg const. and B433(98)150 |        |        |        |        |        |                  |
| SACLAY              | 850 kg.day 1st moment | of time dist. (and others) | 87% | 91% | 92% | 94% | 96% | only stat. |
| LSM Frejus          | 83d x 9.7kg of time dist. |        | 65% | 70% | 62% | 85% | 87% | incl. syst. Astrop Phys 11(99)275 |
| DAMA 0              | 4123 kg.day 1st moment | of time dist. | 88% | 92% | 96% | 98% | 99% | Phys Lett B389(96)757 |
| LNGS                | 83d x 9.7kg of time dist. |        |        |        |        |        |                  |

did not show any indication of modulation.

8. WIMP searches with Xenon Scintillation Detectors

The search for WIMPs with Xenon scintillators benefits of a well-known technique. Moreover, background discrimination can be done better than in NaI. They are also targets of heavy nuclear mass (A ~ 130) for enhancement of the spin-independent coherent interaction.

They have achieved a fairly good level of radiopurity, have a good quenching factor (Q~50%) and a high density (~3gr/cm³). Summing up these properties, one conclude that Xenon scintillators based detectors are a good option to look for WIMPs.

One of the pioneer searches using Xenon is the DAMA liquid-Xenon experiment. The spectra of limits on recoils in WIMP, Xe elastic scattering using PSD and exclusion plots were published in Ref. [46]. Recent results of the DAMA liquid Xenon experiment refers to limits on WIMP, Xe inelastic scattering [47].

The ZEPLIN Program [48] uses a series of Xenon-based scintillators devices able to discriminate the background from the nuclear recoils in liquid or liquid-gas detectors in various ways. Either using the Scintillation Pulse Shape or measuring the scintillation and the ionization (an electric field prevents recombination, the charge being drifted to create a second scintillation pulse), and capitalizing the fact that the primary (direct) scintillation pulse and the secondary scintillation pulse amplitudes differ for electron recoils and nuclear recoils, the secondary scintillation being smaller for nuclear recoils. That feature provides a powerful background rejection. The secondary scintillation photons are produced by proportional scintillation process in liquid-Xenon like in the ZEPLIN-I detector, (where a discrimination factor of 98% is achieved) or by electro luminescence photons in gas-Xenon (like in the case of the ZEPLIN-II detector prototype) in which the electrons (ionization) are drifted to the gas phase where electroluminescence takes place (the discrimination factor being > 99%) [49]. Some prototypes have been tested and various different projects of the ZEPLIN series are underway in Boulby. A recent running has provided a remarkable exclusion plot (see [32]) which traverse entirely the DAMA region as shown in Fig 2. Table 6 is an sketch of the various Xenon experiment or projects.

9. WIMP searches with Time Projection Chambers

DRIFT is a detector project sensitive to directionality [51]. It uses a low pressure (10-40 Torr) TPC with Xenon to measure the nuclear recoil track in WIMP-Nucleus interactions. The direction and orientation of the nuclear recoil provide a characteristic signature of the WIMP. The diffusion constrains the track length observable but DRIFT reduces the diffusion (transversal and longitudinal) using negative ions to drift the ionization instead of drift electrons: gas CS₂ is added to
Table 6
Xenon scintillation experiments

| Experiment and site | Type of detector | Mass (kg) | $E_{thr}$ (keV) | Meth. of discrim | Discr. eff./Reject. factor | BKG at Thr before PSD | Observations |
|---------------------|------------------|----------|----------------|----------------|--------------------------|------------------------|--------------|
| DAMA-Xe LNGS        | Liquid Xe        | 6.5      | 13             | PSD            | 50% (13-15 keV) 0.8 c/keVkgd | Classical search for WIMPs with Xe (since 1993) Phys Lett B389 (96)757 |
| ZEPLIN I Boulby     | Liquid Xe        | 4        | PSD/ION        |                | > 99% goal                  | 1m$^3$ by 2001-2002   |
| ZEPLIN II Boulby    | Two-Phase Xe     | 20-40    | 10 SCI/ION     |                | 10$^{-2}$ c/kg.d 1 kg prototype UCLA-Torino Low field |
| ZEPLIN III Boulby   | Two-Phase Xe     | 6        | SCI/ION improved|                | 10$^{-4}$ c/kg.d 1 kg prototype UCLA-Torino Low field |
| ZEPLIN IV Boulby    | Two-Phase Xe     | 1000     | SCI/ION        |                | 10$^{-4}$ c/kg.d Ext. of Z II |
| KAMIOKA Xe          | Liquid-Gas       | 1        | 99%            | (10-100 keV)   |                          |                        |

Capture electrons and so $CS_{S_2}^{(-)}$ ions are drifted to the avalanche regions (where the electrons are released) for multwire read-out (no magnetic field needed). The negative ion TPC has a millimetric diffusion an a millimetric track resolution. The proof-of-principle has been performed in mini-DRIFTs, where the direction and orientation of nuclear recoils have been seen. The event reconstruction, the measurement of the track length and orientation, the determination of dE/dx and the ionization measurement permit a powerful background discrimination (99.9% gamma rejection and 95% alpha rejection) leading to a rate sensitivity of $R < 10^{-2}$(-3)c/kgday. DRIFT will permit to recognize the forward/backward asymmetry and the nuclear recoils angular distribution, which, as already noted, are the most clear distinctive signatures of WIMPs. That will permit hopefully the identification of WIMP. A DRIFT prototype of 1 m$^3$ is almost completed. A project of 10 m$^3$ (Xe) scaling up the TPC of 1 m$^3$ (Xe) is under way.

10. WIMP searches with metastable particle detectors

WIMP detectors, which use the metastability of the medium where the nuclear targets are embedded, are the (novel) superheated drop detectors (SDD) (like SIMPLE and PICASSO) and the (old) superconducting superheated grains (SSD) (like ORPHEUS). The SDD’s consist of a dispersion of droplets ($\sim 10 \mu m$) of superheated liquid (freon) in a gel matrix. The energy deposition of a WIMP in the droplets produces a phase transition from the superheated to normal state causing vaporization of droplets into bubbles ($\sim 1mm$), detected acoustically. SSD are essentially insensitive to low LET particles ($e$, $\gamma$, $\mu$), and so good for detecting WIMPs and neutrons. See Ref.[52] and [3] for PICASSO.

The Superconducting Superheated Grains (SSG) detectors, like ORPHEUS, is based on the change of phase from the superconducting superheated to the normal state produced by the WIMP energy deposition in micrograins inside a
magnetic field, at very low temperatures. The signal is detected through the disappearance of the Meissner effect. The SSG offer good background rejection (97%) (a single grain is expected to flip per WIMP or nucleon interaction, in contrast to several grains in the case of other particles), and are sensitive to very low energy deposition (as proved in neutron irradiation experiments). An experiment with tin micrograins has just started at the Bern Underground Laboratory (70 m.w.e.)[54,55].

11. Conclusions and outlook

The direct search for WIMP dark matter proceeds at full strength. There are many experiments and projects on direct detection going on. Only a sample of them has been chosen to illustrate the strategies, methods and achievements. The new experiments are focusing in the identification of WIMPs, discriminating the nuclear recoils from the background (rather that in constraining or excluding their parameters space) and looking for distinctive WIMP signals.

Taking also into account the results and perspectives of the direct detection with cryogenic/thermal devices, reviewed by L. Mosca in these Proceedings, the present experimental situation can be summarized as follows: the rates predicted for SUSY-WIMPs extend from 1-10 c/kg/day down to $10^{-4} - 10^{-5}$ c/kg/day, in scatter plots, obtained within MSSM as basic frame implemented in various alternative schemes. A small fraction of this window is testable by some of the leading experiment. The rates experimentally achieved stand around 1 c/kg/day (0.1 c/kg/day at hand) (CDMS, EDELWEISS) and differential rates $\sim 0.1 - 0.05$ c/keVkg/day have been obtained by IGEX and H/M, in the relevant low energy regions. The deepest region of the exclusion plots achieved stands around a few $\times 10^{-6} - 10^{-7}$ pb, for masses 50-200 GeV (EDEL-WEISS and ZEPLIN). The current status of the most relevant exclusion plots (IGEX, DAMA, CDMS, EDELWEISS, ZEPLIN) is depicted comparatively in Fig 2. On the other hand, there exists an unequivocal annual modulation effect (see Fig. 3) reported by DAMA (four yearly periods), which has been shown to the compatible with a neutralino-WIMP, of $m$~50 – 60GeV and $\sigma_n^{SI} \sim 7 \times 10^{-6}$pb. Recent experiments exclude at greater or lesser extend (CDMS, EDELWEISS, ZEPLIN, IGEX) the DAMA region in the case of an assumed purely scalar interaction.
To reach the lowest rates predicted ($10^{-5}$ c/kg/day) in SUSY-WIMP-nucleus interaction, or in other words, to explore coherent interaction cross-sections of the order of $10^{-9} - 10^{-10}$ pb, substantial improvements have been accomplished in pursuing at its best the strategies reviewed in this talk, with special emphasis in discriminating the type of events. These strategies must be focussed in getting a much lower background (intrinsic, environmental, ...) by improving radiopurity and shielding. The nuclear recoil discrimination efficiency should be optimized going from above shieldings. The nuclear recoil discrimination efficiency should be optimized going from above shieldings. The measurement of the parameters used to discriminate background from nuclear recoils should be improved and finally one needs to increase the target masses and guaranty a superb stability over large exposures. With these purposes various experiments and a large R+D activity are under way. Some examples are given in Table 8. The conclusion is that the search for WIMPs is well focused and should be further pursued in the quest for their identification.

Acknowledgments

I wish to thank S. Cebrián and I.G. Irastorza for their invaluable collaboration in the making of the exclusion plots and to J. Morales for useful discussions. The present work was partially supported by the CICYT and MCyT (Spain) under grant number AEN99-1033 and by the EU Network contract ERB FMRX-CT98-0167.

REFERENCES

1. A. Bottino et al. DFTT 35/2000 and references therein. J. Ellis et al. [hep-ph/0007113] and P. Gondolo [hep-ph/0008023].

2. J. R. Primack, D. Seckel and B. Sadoulet, Ann. Rev. Nucl. Part. Sci. 38 (1988) 751. Jungman, M. Kamionkowski and K. Griest, Phys. Rep. 267 (1996) 195. Rep. 267 (1996) 195.

Table 8

| WIMP Direct Detection Prospect |
|-------------------------------|
| BEING INSTALLED/OR PHASE II EXPERIMENTS (To start 2001-2002) |
| CDMS-II (Ge,Sn) Phonons+Ioniz 7 kg, B~10^{-2} - 10^{-3} c/kgd, \( \sigma \sim 10^{-8} \) pb |
| EDELWEISS-II (Ge) Phonons+Ioniz 0.7 kg, B~10^{-2} - 10^{-3} c/kgd, \( \sigma \sim 10^{-8} \) pb (40-200 GeV) |
| CUORICINO TeO2 Phonons 42 kg, B~10^{-2} dru, \( \sigma \sim 0^{-7} \) pb |
| CREST-II CaWO4 Phonons+light, B < 10^{-2} - 10^{-3} dru (15 keV), \( \sigma \sim 10^{-7} - 10^{-8} \) pb (50-150 GeV) |
| IGEX Ge Ioniz 2.1 kg, B< 10^{-1} - 10^{-2} dru, \( \sigma \sim 2 \times 10^{-6} \) pb (40-200 GeV) |
| HDMS Ge Ioniz 0.2 kg, \( \sigma \sim 6 \times 10^{-6} \) pb (20-80 GeV) |
| ANAIS NaI Scintillators 107-150 kg, B(PSD) \leq 0.1 dru, \( \sigma \sim 2 \times 10^{-6} \) pb |
| NAIAID NaI Scintillators 10-50 kg, B(PSD) \leq 0.1 dru, \( \sigma \sim 10^{-6} \) pb (60-200 GeV) |

| IN PREPARATION (To start 2002-2003) |
| LIBRA (DAMA) NaI Scintillators 200 kg |
| GENIUS-TF Ge IONIZ 40 kg, B< 10^{-2} dru, \( E_{Th} = 10 \) keV \( \rightarrow \sigma \sim 10^{-6} \) pb (40-200 GeV), \( E_{Th} = 2 \) keV => \( \sigma \sim 10^{-7} \) pb (20-80 GeV) |
| ZEPLIN-II Xe Two-phase 40 kg, NR discrim\geq 99\%, B< 10^{-2} dru, \( \sigma \sim 10^{-7} \) pb |
| DRIFT-I Xe TPC 1 m^2, B < 10^{-2} dru, \( \sigma \sim 10^{-6} \) pb (80-120 GeV) |

| THE FUTURE (>2005-2007) |
| CUORE TeO2 Phonons 760 kg, \( E_{Th} \sim 2.5 \) keV, B~10^{-4} - 10^{-3} dru, \( \sigma \sim 5 \times 10^{-8} \) pb |
| GENIUS 100 Ge IONIZ 100 kg, \( E_{Th} \sim 10 \) keV |
| (GENINO) B~10^{-3} - 10^{-5} dru, \( \sigma \sim 5 \times 10^{-8} - 2 \times 10^{-9} \) pb |
| GEDEON Ge IONIZ 28-112 kg, B~2 \times 10^{-3} dru (>10 keV) \( \sigma \sim 10^{-7} - 10^{-8} \) pb (40-200 GeV) |

| DRIFT 10 Xe 10 m^2 TPC, \( \sigma \sim 10^{-8} \) pb |
| ZEPLIN-MAX Xe Two-Phase, \( \sigma \sim 10^{-10} \) pb |
| GENIUS Ge IONIZ 1-10 Tons, \( \sigma \sim 10^{-9} - 10^{-10} \) pb |
| DRIFT-1 ton Xe 1 Ton TPC, \( \sigma \sim 10^{-10} - 10^{-11} \) pb |
3. A. Morales. Review Talk at the TAUP 99 Workshop, College de France, Paris. Nucl. Phys. B (Proc. Suppl.) 87 (2000) 477 and Review Talk at the TAUP 2001 Workshop, Laboratori Nazionali del Gran Sasso, Italy, Sept. 2001. Nucl. Phys. B (Proc. Suppl.) 110 (2002) 39.

4. M. W. Goodman, E. Witten, Phys. Rev. D31 (1985) 3059

5. A. K. Drukier et al., Phys. Rev. D33 (1986) 3495.

6. D. N. Spergel, Phys. Rev. D 37 (1988) 1953.

7. P. F. Smith and J. D. Lewin. Phys. Rep. 187 (1990) 203.

8. M. L. Sarsa et al, Phys. Rev. D 56 (1997) 1856.

9. K. Fushimi et al. Phys. Rev. C 47 (1993) R425.

10. R. Bernabei et al, Nucl. Instr. Meth. A482 (2002), 728.

11. Topics in Astroparticles and Underground Physics. In particular in the TAUP 1999 and 2001 Proceedings published in Nucl. Phys B (Proc. Suppl.) vols 87 (2000) and 110 (2002) respectively. See also the Proceedings of the Neutrino 2002 Conference, to appear in Nucl. Phys B (Proc. Suppl.).

12. J. Copi, J. Heo and L. M. Krauss, Phys. Lett. B 461 (1999) 43.

13. S. Cebrián et al. Astrop. Phys. 10 (1999) 361. S. Cebrián et al. Nucl. Instr. Meth. A 444 (2000) 315. S. Cebrián et al. Astrop. Phys. 15 (2001) 79. S. Cebrián et al. Nucl. Phys. B (Proc. Suppl.) 110 (2002) 97.

14. S. P. Ahlen et al., Phys. Rev. D 33 (1987) 603. and A. K. Drukier et al., Nucl. Phys. B (Proc. Suppl.) 28A (1992) 293.

15. J. Morales et al., Nucl. Instrum. & Meth. A321 (1992) 410.

16. E. García et al., Nucl. Phys. B (Proc. Suppl.) 28A (1992) 286 and Phys. Rev. D51 (1995) 1458.

17. D. O. Caldwell et al., Phys. Rev. Lett. 61 (1988) 510.

18. D. Reusser et al., Phys. Lett. B 255 (1991) 143.

19. M. Beck et al., Phys. Lett. B 336 (1994) 141.

20. S. Cebrián et al., New Journal of Physics 2 (2000) [http://www.njp.org].

21. A. Morales. "WIMP searches at Canfranc with Germanium Detectors". Proc. of South Carolina Symposium on Neutrino Physics, Ed. H. Kuborera et al., World Scientific Pub. 2000.

22. D. González et al., Proc. TAUP 99 Workshop, Collège de France, Paris, Nucl. Phys. B (Proc. Suppl.) 87 (2000) 278.

23. C. Aalseth et al., Phys. Rev. C 59 (1999) 2108.

24. A. Morales et al. [IGEX Collaboration], Phys. Lett. B 489 (2000) 268 [hep-ex/0002053].

25. A. Morales et al. [IGEX Collaboration], [hep-ex/0110061]. Phys. Lett. B 532 (2002) 8.

26. L. Baudis et al., Phys. Rev. D 59 (1999) 022001.

27. J. Engel, Phys. Lett. B 264 (1991) 114.

28. R. Bernabei et al., Phys. Lett. B 450 (1999) 448 and Phys. Lett. B480 (2000) 23.

29. See I. G. Irastorza. Thesis Disertation. Univ. of Zaragoza. April 2001.

30. R. Abusaidi et al. [CDMS Collaboration], Phys. Rev. Lett. 84 (2000) 5699 [astro-ph/0002471].

31. A. Benoit et al. [EDELWEISS Collaboration], Phys. Lett. B 513 (2001) 15 [astro-ph/0106094].

32. I. Liubarski. Contributed Poster to the Neutrino 2002 Conference. Munich, May 2002. To appear in Nucl. Phys. Proc. Suppl.

33. R. Bernabei et al., Phys. Lett. B379 (1996) 299.

34. A. Morales et al., GEDEON, a project for WIMP searches with a set of natural abundance Ge diodes in a single cryostat. Preliminary Study for Submission to CICYT (Spain), January 1999.

35. S. Cebrian, private communication.

36. S. Cebrian et al., Astropart. Phys. 14 (2001) 339.

37. K. Freese et al, Phys. Rev. D 27 (1988) 3388.

38. L. Baudis et al., Phys. Rev. D 63 (2000)
39. L. Baudis et al., [hep-ex/0012022]. NIM A 481 (2002) 149.
40. S. Cebrian et al., Nucl. Phys. B (Proc. Suppl.) 110 (2002) 94.
41. P. F. Smith et al., Phys. Lett. B 379 (1996) 299 and N. J. C. Spooner et al., Phys. Lett. B 473 (2000) 330.
42. G. Gerbier et al., Astrop. Phys. 11 (1999) 287.
43. K. Fushimi et al., Astrop. Phys. 12 (2000) 185.
44. E. Fiorini, Phys. Rep. 307 (1998) 309. Letter of intent to the Gran Sasso Scientific Committee and to the Funding Authorities, March, 2001.
45. A. Giuliani et al, Nucl. Phys. B (Proc. Suppl.) 110 (2002) 64.
46. R. Bernabei et al., Phys. Lett. B 436 (1998) 379.
47. R. Bernabei et al., NJP 2 (2000) 15.1.
48. N. J. C. Spooner, The Future of Particle Physics, Snowmass 2001.
49. R. Luscher et al., Nucl. Phys. B (Proc. Suppl.) 95 (2001) 233.
50. D. Cline, ZEPLIN-IV. Contribution to the Snowmass2001 Workshop, [astro-ph/0108045].
51. C. J. Martoff et al., Nucl. Instr. and Meth. in Phys. Res. A 440 (2000) 355.
52. J. I. Collar et al., NJP 2 (2000) 14.
53. V. Zacek, Nucl. Phys. B (Proc. Suppl.) 91 (2001) 368.
54. B. van den Brandt et al., Nucl. Phys. B (Proc. Suppl.) 87 (2000) 117.
55. K. Pretzl, Nucl. Instr. and Meth. in Phys. Res. A 454 (2000) 114.