Searching for WIMP Dark Matter: The case for Germanium Ionization Detectors*

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Abstract

An overview of the main strategies followed in the search for non-baryonic particle dark matter in the form of WIMPs is given. To illustrate these searches the case for Germanium ionization detectors is selected.

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 critical density of a flat universe ($\Omega = 1$). The current picture describes an universe consisting of unknown species of Dark Energy ($\Omega_\Lambda \sim 70\%$) and Dark Matter ($\Omega_M \sim 25 – 30\%$) of which less than ~ 5% is of baryonic origin. Most of the Dark Matter would then be made of non-baryonic particles filling the galactic halos, at least partially, according to a variety of models. Weak Interacting Massive (and neutral) Particles (WIMPs) are favourite candidates to such non-baryonic components. The lightest stable particles of supersymmetric theories, like the neutralino, describe a particular class of 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. 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 (CAPRICE, BESS, AMS, GLAST, VERITAS, MAGIC...), or by searching in large underground detectors (SUPERKAMIOKANDE, SNO, SOUDAN, MACRO) or underwater neutrino telescopes (BAIKAL, AMANDA, ANTARES, NESTOR) for upward-going muons produced by the energetic neutrinos emerging as final products of the WIMPs annihilation in celestial bodies (Sun, Earth...). This talk will deal with the direct detection of WIMPs.

The direct detection of WIMPs relies in the measurement of the WIMP elastic scattering off the target nuclei of a suitable detector. Pervading the galactic halos, slow moving ($\sim 300 \text{ km/s}$), and heavy ($10 \sim 10^3 \text{ GeV}$) WIMPs could make a nucleus recoil with a small energy of a few keV ($T \sim (1 – 100) \text{ keV}$), at a rate which depends of the type of WIMP and interaction. Only a fraction of the recoil, QT, 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

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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 make 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 [30]. In fact, it is not higher than $10^{-2}$ c/kg day, for the neutralino parameters which provide the most favourable relic density ($\Omega h^2$). Due to such small rate and small energy deposition produced by the WIMP elastic scattering, the direct search for particle dark matter through their scattering by nuclear targets requires ultralow background detectors of a very low energy threshold. Moreover, the (almost) exponentially decreasing shape of the predicted nuclear recoil spectrum mimics that of the low energy background registered by the detector. All these features together make the WIMP detection a formidable experimental challenge.

Customarily, 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. That excludes, for each mass $m$, those particles with a cross-section above the contour line $\sigma(m)$. The level of background sets, consequently, the sensitivity of the experiment in eliminating candidates or in constraining their masses and cross sections.

However, this mere comparison of the expected signal with the experimentally observed spectrum will not be able to detect the WIMP, because such spectrum, even extremely small, could still be due to pure background sources. In other words, it would be difficult to be convinced that such signal is due to WIMPs and not to mere background sources. A convincing proof of the detection of WIMPs would need to find unique signatures in the data characteristic of them and not of the background. There exist some temporal or spatial asymmetries specific of the WIMP interaction, which cannot 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. The only distinctive signature investigated up to now is a predicted annual modulation of the WIMP signal rate due to the seasonal variation produced by the Earth’s motion with respect to the Sun. Such a seasonal effect has been found by the DAMA experiment at the 3$\sigma$ level and has been associated to the existence of a WIMP.

The detectors used so far 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), calcium fluoride scintillators (MILAN, OSAKA, ROMA), thermal detectors (bolometers) with sapphire absorbers (CRESST, ROSEBUD), with telurite 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 detectors and techniques are entering the stage. 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 4 gives an overview of the experiments on direct detection of WIMPs currently in operation or in preparation. A review of neutralino dark matter can be found in Ref [1]. WIMP direct detection are reviewed, for instance in Ref [2] and [3]. Recent results are given in Ref [4].

2 Strategies for WIMP detection

The smallness and rarity of WIMP signals dictate the experimental strategies for their detection: reduce first the background, by controlling the radiopurity of the detector, its components, the shielding and the environment. The best radiopurity has been obtained in conventional Ge experiments (IGEX, H/M). In the case of the NaI scintillators (DAMA, UKDM, ANAIS), the achieved backgrounds are still one order of magnitude worse than those reached in Ge, but the use of new radiopure powder in the crystals has lead to
substantial improvements (DAMA). The next step is to use discrimination mechanisms able to distinguish electron recoils (tracers of the background) from nuclear recoils (originated by WIMPs or neutrons). Two types of techniques have been applied for such purpose: a statistical pulse shape analysis (PSD) based on the different timing behaviour of both types of pulses and a background rejection method based on the identification (on an event-by-event basis) of the nuclear recoils, by measuring at the same time two different mechanisms of energy deposition, like the ionization (or scintillation) and heat, capitalizing the fact that for a given deposited energy (measured as phonons) the recoiling nucleus ionizes less than the electrons. Examples of PSD are UKDMC, Saclay, DAMA and ANAIS, whereas the event by event discrimination has been successfully applied in CDMS and EDELWEISS by measuring ionization and heat and now in CRESST and ROSEBUD by measuring light and heat.

A promising 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 gammas allowing their discrimination.

Another technique is to discriminate gamma background from neutrons (and so WIMPs) using threshold detectors—like neutron dosimeters—which are blind to most of the low Linear Energy Transfer (LET) radiation ($e, \mu, \gamma$). Detectors which use superheated droplets which vaporize into bubbles by the WIMP (or other high LET particles) energy deposition are SIMPLE and PICASSO. 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).

Obviously one should try to make detectors of very low energy threshold and high efficiency to see most of the signal spectrum, not just the tail. That is the case for the bolometer experiments which seen efficiently the energy delivered by the WIMP (quenching factor is unity), (MIBETA, CRESST, ROSEBUD, CUORICINO, CDMS and EDELWEISS).

After the process of reducing and identifying the background is driven to its best, then one should search for distinctive signatures of the dark matter particles to prove that you are, indeed, seeing a WIMP. Identifying labels are derived from the Earth motion through the galactic halo, which produces two assymetries distinctive of WIMPs: First, the Earth orbital motion around the sun has a summer-winter variation which results in a small (5%) annual modulation of the WIMP interaction rates; and second, the Earth (and solar system) motion through the galactic centre produces a large ($\sim 1$) directional assymetry forward-backward of the recoiling nucleus. The annual modulation signature has been already explored. Pioneering searches for WIMP annual modulation signals were carried out in Canfranc (NaI-32), Kamioka (ELEGANTS) and Gran Sasso (DAMA-Xe). Recently the DAMA experiment at Gran Sasso, using a set of NaI scintillators reported in 1997 and 2000 an annual modulation effect of at the 3$\sigma$ level interpreted as due to a WIMP of about 60 GeV of mass and scalar cross-section on protons of $\sigma_p = 7 \times 10^{-6}$ picobarns. As far as the forward-backward assymetry of the signal is concerned the DRIFT project will search for it. Information and current results of the experiments mentioned above can be found in References [4] and [5].

In particular, in the underground facility of the Canfranc Tunnel (Spain), various of the techniques mentioned above are currently employed in a search for WIMPs: Ge ionization detectors, (COSME and IGEX), Sodium iodine scintillators (NaI-32 and ANAIS), thermal detectors with $\text{Al}_2\text{O}_3$ and Ge absorbers (ROSEBUD-I) as well as and with calcium tungstate and BGO scintillating bolometers (ROSEBUD-II). To illustrate how these searches proceed we will present the case for Ge detectors, and will describe its status, achievements and results. As one of the main achievements in Ge experiments is their low radioactive background, essential ingredient in the search for dark matter, we will illustrate it with a saga of Germanium experiments performed in Canfranc and the successive suppresion of the background obtained. Such reduction has provided the lowest raw background rate obtained so far and, consequently, the stringest exclusion plots ever derived with ionization detectors.
3 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, as by-products of 2β-decay dedicated experiments. The exclusion plots $\sigma(m)$ for spin-independent couplings obtained by former Ge experiments [PNNL/USC/Zaragoza (TWIN and COSME-1), UCSB, CALT/NEU/PSI, H/M] are still remarkable and have not been surpassed till recently by NaI experiments (DAMA) using statistical pulse shape discrimination (PSD) or by cryogenic experiments measuring both heat and ionization like CDMS and EDELWEISS. Table 5 shows the Germanium ionization detector experiments currently in operation.

A Ge detector of natural isotopic abundance (COSME) of the U. Zaragoza / U. S. Carolina / PNNL Collaboration and another one (RG-II) made of enriched $^{76}$Ge of the IGEX Collaboration are being used in Canfranc to search for WIMPs interacting coherently with the Ge nuclei of the detectors.

The COSME detector was fabricated at Princeton Gamma-Tech, Inc. in Princeton, New Jersey, using germanium of natural isotopic abundance. The refinement of newly-mined germanium ore to finished metal for this detector was expedited to minimize production of cosmogenic $^{68}$Ge. The detector is a p-type coaxial hyperpure natural germanium crystal with a mass of 254 g and an active mass of 234 g which has a long term resolution of 0.43 keV full width at half maximum (FWHM) at the 10.37 keV gallium X-ray. In its first Canfranc installation (at 675 m.w.e) the detector was placed within a shielding of 10 cm of 2000 yr. old (Roman) lead (inner layer) plus 20 cm of low activity lead (about 70 yr old). A 3 mm thick PVC box sealed with silicone closed the lead shielding to purge the radon gas. The PVC box was covered by 1 mm of cadmium and 20 cm of paraffin and borated polyethylene. All the shielding and mounting was supported by 10 cm of vibrational and acoustic insulator sandwiched within two layers of 10 cm of wood mounted on a floor of concrete (20 cm). It was operated in the former Canfranc underground facility at 675 m.w.e. in a small gallery of the Canfranc railway tunnel in the Spanish Pyrenees closed to the traffic.

In that set-up, the energy threshold was $E_{\text{thr}} = 1.6$ keV and the background at threshold was about 10 counts keV$^{-1}$ kg$^{-1}$ day$^{-1}$. After about 500 days of data taking (referred as COSME-1 experiment) no signal originated by WIMP appeared and, from the background spectrum, an exclusion plot in the cross-section versus WIMP masses plane was derived, assuming WIMP-matter spin-independent couplings. In the COSME-1 data, the energy range chosen to derive the exclusion plot was from 1.6 to 8 keV where the background was, approximately, 5 counts/(keV kg day). In spite of such modest figure, the results
after 130 kg day of exposure improved the exclusion plots at low masses (from 9 to 20 GeV) obtained with other Ge experiments because of the low threshold energy of COSME-1.

The COSME detector has been reinstalled, in better background conditions in the new Canfranc Underground Laboratory LSC (at 2450 m.w.e.) inside a Marinelli beaker in Roman lead (COSME-2) in a common shielding (described later) together with the three 2.1 kg enriched germanium detectors of IGEX (the International Germanium Experiment on Double Beta Decay). In its new installation, COSME-2 has an energy threshold of $E_{\text{thr}} = 2.5$ keV, and an energy resolution of $\Gamma(\text{FWHM}) = 0.4$ keV at 10 keV. The average background rate, in 311 days of exposure (Mt=72.8 kg day) is 0.6 c/(keV kg day) from 2 to 15 keV and 0.3 c/(keV kg day) from 15 to 30 keV which is significantly better (more than one order of magnitude) than in COSME-1. The COSME-2 spectrum is shown in Fig. 1 together with that of COSME-1, to show the remarkable background reduction obtained in the new set-up and shielding and the disappearance of the cosmogenically induced peaks in the 8-10 keV energy region due to the about ten years elapsed between the two experiments. The numerical data of COSME 2 are given in Table 1.

| E (keV) | counts | E (keV) | counts | E (keV) | counts |
|---------|--------|---------|--------|---------|--------|
| 2.5     | 1098   | 18.5    | 25     | 34.5    | 21     |
| 3.5     | 76     | 19.5    | 19     | 35.5    | 13     |
| 5.5     | 57     | 31.5    | 20     | 37.5    | 12     |
| 7.5     | 56     | 22.5    | 18     | 38.5    | 14     |
| 8.5     | 51     | 24.5    | 17     | 39.5    | 20     |
| 9.5     | 45     | 25.5    | 20     | 41.5    | 17     |
| 10.5    | 56     | 26.5    | 22     | 40.5    | 13     |
| 11.5    | 46     | 27.5    | 23     | 42.5    | 17     |
| 12.5    | 34     | 28.5    | 19     | 44.5    | 20     |
| 13.5    | 30     | 29.5    | 19     | 45.5    | 18     |
| 14.5    | 34     | 30.5    | 19     | 46.5    | 48     |
| 15.5    | 38     | 31.5    | 15     | 47.5    | 20     |
| 16.5    | 30     | 32.5    | 27     | 48.5    | 17     |
| 17.5    | 19     | 33.5    | 22     | 49.5    | 19     |

Table 1: Low-energy data from the COSME-2 detector (Mt = 73 kg-d).

The International Germanium Experiment (IGEX) is an experiment which was designed to investigate the double beta decay of Germanium. It uses three enriched detectors of $^{76}$Ge of $\sim$2.1 Kg each, and it has been described in detail elsewhere [4][13]. One of these detectors, RG-II, has been recently prepared for use at low energies in typical WIMP searches (referred to as IGEX-DM).

The IGEX detectors (and so RG-II) were fabricated at Oxford Instruments, Inc., in Oak Ridge, Tennessee. Russian GeO$_2$ powder, isotopically enriched to 86% $^{76}$Ge, was purified, reduced to metal, and zone refined to $\sim 10^{13}$ p-type donor impurities per cubic centimeter by Eagle Picher, Inc., in Quapaw, Oklahoma. The metal was then transported to Oxford Instruments by surface in order to minimize activation by cosmic ray neutrons, where it was further zone refined, grown into crystals, and fabricated into detectors. All of the cryostat parts were electroformed using a high purity OFHC copper/CuSO$_4$/H$_2$SO$_4$ plating system. The solution was continuously filtered to eliminate copper oxide, which causes porosity in the copper. A Ba(OH)$_2$ solution was added to precipitate BaSO$_4$, which is also collected on the filter. Radium in the bath exchanges with the barium on the filter, thus minimizing radium contamination in the cryostat parts. The CuSO$_4$ crystals were purified of thorium by multiple recrystallization.

The RG-II detector, has a mass of $\sim$ 2.2 kg, and an active mass of 2.0 kg, as measured with a collimated source of $^{152}$Eu in the Canfranc Laboratory, in agreement with the Oxford Instruments efficiency measurements. The full-width at half-maximum (FWHM) energy resolution of RG-II is 2.37 keV.
at the 1333-keV line of $^{60}$Co. Energy calibration and resolution measurements were made every 7–10 days using the lines of $^{22}$Na and $^{60}$Co. Calibration for the low energy region was extrapolated using the X-ray lines of Pb. The first-stage field-effect transistor (FET) is mounted on a Teflon block a few centimeters from the central contact of the germanium crystal. The protective cover of the FET and the glass shell of the feedback resistor have been removed to reduce radioactive background. This first-stage assembly is mounted behind a 2.5-cm-thick cylinder of archaeological lead to further reduce background. Further stages of preamplification are located at the back of the cryostat cross arm, approximately 70 cm from the crystal. The detector has preamplifier modified for the pulse-shape analysis.

The detectors shielding (shared by COSME, RG-II and two other IGEX detectors) is as follows, from inside to outside. The innermost shield consists of 2.5 tons of 2000-year-old archaeological lead forming a 60-cm cube and having $< 9$ mBq/kg of $^{210}$Pb($^{210}$Bi), $< 0.2$ mBq/kg of $^{238}$U, and $< 0.3$ mBq/kg of $^{232}$Th. The detectors fit into precision-machined holes in this central core, which minimizes the empty space around the detectors available to radon. Nitrogen gas, at a rate of 140 l/hour, evaporating from liquid nitrogen, is forced into the detector chambers to create a positive pressure and further minimize radon intrusion. The archaeological lead block is centered in a 1-m cube of 70-year-old low-activity lead($\sim 10$ tons) having $\sim 30$ Bq/kg of $^{210}$Pb. A minimum of 15 cm of archaeological lead separates the detectors from the outer lead shield. A 2-mm-thick cadmium sheet surrounds the main lead shield, and two layers of plastic seal this central assembly against radon intrusion. A cosmic muon veto covers the top and sides of the central core, except where the detector Dewars are located. The veto consists of BICRON BC-408 plastic scintillators 5.08 cm $\times$ 50.8 cm $\times$ 101.6 cm with surfaces finished by diamond mill to optimize internal reflection. BC-800 (UVT) light guides on the ends taper to 5.08 cm in diameter over a length of 50.8 cm and are coupled to Hamamatsu R329 photomultiplier tubes. The anticoincidence veto signal is obtained from the logical OR of all photomultiplier tube discriminator outputs. An external polyethylene neutron moderator 20 cm thick (1.5 tons) completes the shield. The entire shield is supported by an iron structure resting on noise-isolation blocks. The experiment (referred to as IGEX-2000) is located in a room isolated from the rest of the laboratory and has an overburden of 2450 m.w.e., which reduces the muon flux down to a measured $2 \times 10^{-7}$ cm$^{-2}$s$^{-1}$.

The data acquisition system is based on standard NIM electronics. It has been implemented by splitting the normal preamplifier output pulses of each detector and routing them through two Canberra
Table 2: Low-energy data from the IGEX RG-II detector (Mt = 60 kg-d), labelled IGEX-2000.

| E (keV) | counts | E (keV) | counts | E (keV) | counts |
|--------|--------|--------|--------|--------|--------|
| 4.5    | 44     | 19.5   | 9      | 34.5   | 3      |
| 5.5    | 23     | 20.5   | 5      | 35.5   | 2      |
| 6.5    | 29     | 21.5   | 3      | 36.5   | 1      |
| 7.5    | 17     | 22.5   | 4      | 37.5   | 4      |
| 8.5    | 8      | 23.5   | 4      | 38.5   | 2      |
| 9.5    | 14     | 24.5   | 0      | 39.5   | 3      |
| 10.5   | 12     | 25.5   | 2      | 40.5   | 1      |
| 11.5   | 14     | 26.5   | 1      | 41.5   | 5      |
| 12.5   | 10     | 27.5   | 2      | 42.5   | 0      |
| 13.5   | 5      | 28.5   | 3      | 43.5   | 3      |
| 14.5   | 3      | 29.5   | 1      | 44.5   | 4      |
| 15.5   | 3      | 30.5   | 2      | 45.5   | 3      |
| 16.5   | 10     | 31.5   | 2      | 46.5   | 10     |
| 17.5   | 3      | 32.5   | 3      | 47.5   | 1      |
| 18.5   | 5      | 33.5   | 2      | 48.5   | 2      |

2020 amplifiers having different shaping times enabling noise rejection as first applied in Ref [8]. These amplifier outputs are converted using 200 MHz Wilkinson-type Canberra analog-to-digital converters, controlled by a PC through parallel interfaces. For each event, the arrival time (with an accuracy of 100 µs), the elapsed time since the last veto event (with an accuracy of 20 µs), and the energy from each ADC are recorded. For a total counting rate smaller than 1 Hz, the dead time is negligible. The muon veto anticoincidence was done off-line with a software window of 240 µs.

For the data taken in a new set-up, described below, (and referred to as IGEX-2001) [21], the acquisition system previously used has been complemented by recording also the pulse shapes of each event before and after amplification by mean of two 800 MHz LeCroy 9362 digital scopes. These are analysed one by one by means of a method based on wavelet techniques which allows us to access the probability of this pulse to have been produced by a random fluctuation of the baseline. This probability is used as a criterium to reject events coming from electronic noise or microphonics [28]. According to the calibration of the method, it works very efficiently for noise events above 4 keV.

4 Results obtained from the IGEX set-ups [20][21]

The detector IGEX-RG-II in both set-ups features an energy threshold of 4 keV and an energy resolution of 0.8 keV at the 75 keV Pb x-ray line. We will show first the results obtained with the set-up and shielding described above. They correspond to 30 days of analyzed data (Mt=60 kg-days) and they will be labelled IGEX-2000 (Table 2 and Fig. 2). The background rate recorded was \(~ 0.4 \text{ c/(keV-kg-day)}\) between 4–10 keV, \(~ 0.12 \text{ c/(keV-kg-day)}\) between 10–20 keV, and \(~ 0.05 \text{ c/(keV-kg-day)}\) between 20–40 keV. Fig. 2 shows the RG-II 30-day spectrum in this shielding. The numerical data are given in Table 2. The corresponding \(\sigma(m)\) exclusion plot is given in Fig. 3 following the procedure explained below. Earlier results from the COSME detector (COSME-1) [8][9] are included in Fig. 3 (dot-dashed line). The recent results obtained in its current set-up (COSME-2) [6][16], corresponding to the spectrum of 311 days depicted in Fig. 1 and listed in Table 1 are also shown in its corresponding \(\sigma(m)\) exclusion contour of Fig. 3 (thick-dashed line).

The exclusion plots resulting from the IGEX-2000 data are derived from the recorded spectrum Fig. 2 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. 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
Figure 3: IGEX-DM exclusion plot for spin-independent interaction obtained from Canfranc IGEX-2000 Ge detector (thick solid line). Results obtained in other Germanium experiments are also shown: Canfranc COSME-1 data (dot-dashed line), recent COSME-2 data (thick dashed line), and the previous Ge-combined bound (thin dashed line) obtained for the other Ge experiments — including the last Heidelberg-Moscow data. The result of the DAMA NaI-0 experiment (thin solid line) is also shown. The “triangle” area corresponds to the (3σ) annual modulation effect reported by the DAMA collaboration (including NaI-1,2,3,4 runnings). The IGEX-DM projection (dotted line) is shown for 1 kg-year of exposure with a background rate of 0.1 c/(keV-kg-day).

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 $v_{\text{rms}} = 270$ 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, assuming a dominant scalar interaction. The Helm parameterization is used for the scalar nucleon form factor, and the recoil energy dependent ionization yield used is the same that in Ref. $\text{[18]}$, $E_{\text{vis}} = 0.14(E_{\text{REC}})^{1.19}$. The exclusion plots obtained from the COSME-2 spectrum (Fig. 1 and Table 1) and from COSME-1 (Fig. 1) have been calculated, as previously noted, in the same way as for IGEX. As shown in Fig. 3, the IGEX-2000 results (thick-solid line) exclude WIMP-nucleon cross-sections above $1.3 \times 10^{-8}$ nb for masses corresponding to the 50 GeV DAMA region. Also shown is the combined germanium contour (thin-dashed line), including the last Heidelberg-Moscow data (recalculated from the original energy spectra with the same set of hypotheses and parameters), the DAMA experiment contour plot derived from Pulse Shape Discriminated spectra, and the DAMA region corresponding to their reported annual modulation effect. The IGEX-2000 exclusion contour improves that of other Germanium experiments for masses between 20 GeV and 200 GeV, which includes the mass region corresponding to the neutralino tentatively assigned to the DAMA modulation effect and results from using only raw data without background subtraction. The COSME-2 exclusion contour also slightly improves the Ge-combined plot for masses between 20 and 40 GeV.

Then, a new set-up was constructed, with the purpose of further improving the background. In particular all the detectors except IGEX RG-II were removed from the shielding, leaving RG-II alone. A new, thorough cleaning of the inner layers of the bricks of lead was performed, and the free space left was stretched. In this new set-up, the detector RG-II is surrounded by not less than 40-45 cm of lead of which 25 cm are archaeological. Also the muon veto covers now more completely the ensemble, because
Table 3: Low-energy data from the IGEX RG-II detector (Mt = 80 kg d) (IGEX-2001).

| E (keV) | counts | E (keV) | counts | E (keV) | counts |
|--------|--------|--------|--------|--------|--------|
| 4.5    | 18     | 19.5   | 4      | 34.5   | 4      |
| 5.5    | 25     | 20.5   | 5      | 35.5   | 4      |
| 6.5    | 16     | 21.5   | 1      | 36.5   | 6      |
| 7.5    | 11     | 22.5   | 4      | 37.5   | 3      |
| 8.5    | 23     | 23.5   | 4      | 38.5   | 3      |
| 9.5    | 9      | 24.5   | 4      | 39.5   | 3      |
| 10.5   | 12     | 25.5   | 4      | 40.5   | 5      |
| 11.5   | 17     | 26.5   | 4      | 41.5   | 4      |
| 12.5   | 12     | 27.5   | 9      | 42.5   | 0      |
| 13.5   | 7      | 28.5   | 4      | 43.5   | 2      |
| 14.5   | 6      | 29.5   | 3      | 44.5   | 3      |
| 15.5   | 6      | 30.5   | 2      | 45.5   | 5      |
| 16.5   | 8      | 31.5   | 2      | 46.5   | 2      |
| 17.5   | 6      | 32.5   | 1      | 47.5   | 3      |
| 18.5   | 1      | 33.5   | 1      | 48.5   | 4      |

The energy threshold of the detector is, as in previous runnings, 4 keV and the FWHM energy resolution at the 75 keV Pb X-ray line is 800 eV. The background rate recorded was $\sim 0.21 \text{ c/keV/kg/day}$ between 4–10 keV, $\sim 0.10 \text{ c/keV/kg/day}$ between 10–20 keV, and $\sim 0.04 \text{ c/keV/kg/day}$ between 25–40 keV. As it can be seen, the background below 10 keV has been substantially reduced (about a factor 50%) with respect to that obtained in the previous set-up of IGEX-2000, essentially due to the improved shielding (both in lead and in polyethylene-water). This suggests that the neutrons could be an important component of the low-energy background in IGEX.

The new exclusion plot derived in this improved conditions IGEX-2001 is shown in Fig. 5 (thick solid line). It improves the IGEX-2000 exclusion contour (thick dashed line) as well as that of the other previous germanium ionization experiments (and in particular that of the last result of Heidelberg-Moscow experiment now specifically depicted by the thick dotted line) for a mass range from 20 GeV to 200 GeV, which encompass, as already said, that of the DAMA mass region. In particular, this new IGEX result excludes WIMP–nucleon cross-sections above $7 \times 10^{-6} \text{ pb}$ for masses of 40-60 GeV and enters the DAMA region. IGEX excludes the upper left part of this region. That is the first time that a direct search experiment without background discrimination, but with very low (raw) background, enters such region. Also shown for comparison are the contour lines of the other experiments, CDMS and EDELWEISS (thin dashed line), which have entered that region by using bolometers which also measure ionization. The DAMA region (closed line) corresponding to the $3\sigma$ annual modulation effect reported by that experiment and the exclusion plot obtained by DAMA NaI-0 (thin solid line) by using statistical pulse shape discrimination are also shown. A remark is in order: for CDMS two contour lines have been depicted according to a recent recommendation, the exclusion plot published in Ref. (thin dotted line) and the CDMS expected sensitivity contour (thin dot-dashed line).

Data collection is currently in progress and some strategies are being considered to further reduce the low energy background. Another 50 % reduction from 4 keV to 10 keV (which could be reasonably expected) would allow to explore practically all the DAMA region in 1 kg y of exposure. In the case of reducing the background down to the flat level of 0.04 c/kg/keV/day (currently achieved by IGEX for
energies beyond 20 keV), the DAMA region would be widely surpassed. In Figure 4 we plot the exclusions obtained with a flat background of 0.1 c/kg/keV/day (dot-dashed line) and of 0.04 c/kg/keV/day (solid line) down to the current 4 keV threshold, for an exposure of 1 kg year. As can be seen, the complete DAMA region \((m=52^{+10}_{-8} \text{ GeV}, \sigma=(7.2^{+0.4}_{-0.9}) \times 10^{-9} \text{ nb})\) could be tested with a moderate improvement of the IGEX performances.

### Ge IONIZATION EXPERIMENTS

| EXPERIMENT AND SITE | M (kg) | \(E_{\text{en}}(\text{keV})\) | \(Q-0.25\) | \(T (\text{keV})\) | LOW ENERGY AVERAGE \(B/(c/\text{keV Kg day})\) | OBSERVATIONS |
|---------------------|--------|----------------|-------------|-------------|----------------------------------|-------------|
| COSME-II LSC, Canfranc | 0.23 \(\pm\) 0.33 \(\text{kg}\) | 2.5 | 0.4 \(\mu\)t 10 keV | 0.6 \(\pm\) 0.15 \(\text{keV}\) | Good exclusions for low mass WIMPs |
| IGEX LSC, Canfranc | 2.1 | 9 | 0.16 \(\mu\)t 15 keV | 0.10 \(\pm\) 0.20 \(\text{keV}\) | 1 detector from IGEX enriched \(^{76}\text{Ge}\) set \((2\beta)\) |
| H/M LNGS | 2.76 | 9 | 2.4 \(\mu\)t 727 \(\text{keV}\) | 0.04 \(\pm\) 0.04 \(\text{keV}\) | 1 detector from H/M enriched \(^{76}\text{Ge}\) set \((2\beta)\) |
| HDMS LNGS | 8.0 | 7.5 | 0.2 \(\mu\)t 100 \(\text{keV}\) | 0.09 \(\pm\) 0.00 \(\text{keV}\) | Small detector inside a well-type Ge outer crystal |
| GENIUS-TP In preparation LNGS | 40 | 9 | 0.05 \(\mu\)t 120 \(\text{keV}\) | COAL \(10^{-8}\) \(\text{keV}\) | 14 Ge crystals embedded in liquid nitrogen, housed in zone-refined Ge bricks |
| GENIUS Project PROJECT | 100 | 12 | 12 \(\mu\)t 100 \(\text{keV}\) | COAL \(10^{-8}\) \(\text{keV}\) | Large set of naked p-type Ge detectors in LN; |
| GEDEON Project LSC, Canfranc | 84 \text{ bas}(7130\text{ kg}) | 1-2 \(\mu\)t 10 \(\text{keV}\) | COAL \(10^{-12}\) \(\text{keV}\) | 28 Ge diodes in one single cryostat. Three sets in archaeological lead and pure graphite shielding. |

Table5

A new experimental project on WIMP detection using larger masses of Germanium of natural isotopic abundance (GEDEON, GERmanium DEtectors in ONe cryostat) is planned\(^{[23]}\). It will use the technology...
developed for the IGEX experiment and it would consist of a set of $\sim 1$ kg germanium crystals, of a total mass of about 28 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 (dimensions 20 cm diameter $\times$ 32 cm long) hosting 28 germanium crystals which share the same common copper cryostat (0.5 mm thick). The Ge crystals, are arranged in four plates 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 background in the $1 \sim 50$ 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\cite{29}. 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 hopefully 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 background of the GEDEON unit cell (28 crystals) is given in Fig. 7. A detailed study is in progress to assess the physics potential of this device. The exclusion plot which could be expected with such proviso for 24 kg y of exposure is shown in the Figure 6. Moreover, following the calculations presented in\cite{26}, GEDEON would be massive enough to search for the WIMP annual modulation effect\cite{27} and explore positively an important part of the WIMP parameter space including the DAMA region. A second phase of GEDEON with four cryostats (112 detectors and

![Figure 5](image-url)
Figure 6: IGEX-DM projections are shown for a flat background rate of 0.1 c/keV/kg/day (dot-dashed line) and 0.04 c/keV/kg/day (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.

Figure 7: Montecarlo estimated background of the GEDEON detector project (energy interval 0—50 keV).

a total mass of 92 kg of Ge) is also being considered.

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| LABORATORY         | EXPERIMENT |     | TECHNIQUE                                                                 |
|-------------------|------------|-----|---------------------------------------------------------------------------|
| BAKSAN (Russia)   | IGEX       | 3x1| Kg Ge-ionization                                                          |
| BERN (Switzerland)| ORPHEUS    | (SSD)| Superconducting Superheated Detector, 0.45 Kg Tin                        |
| DOI-LBY (UK)      | NaI        |    | NaI scintillators of few Kg (recently completed)                          |
|                   | NAID       |    | NaI unencapsulated scintillators (50 Kg)                                  |
|                   | ZEPLIN     |    | Liquid-Gas Xe scintillation/ionization I: 4 Kg single phase               |
|                   | DRIFT      |    | II: 30 Kg Two phase                                                      |
|                   |            |    | Low pressure Xe TPC (in preparation) 1 m$^3 \rightarrow$ 10 m$^3$        |
| CAMBRANG (Spain)  | COSME      | 234| g Ge ionization                                                           |
|                   | IGEX       | 2.1| Kg Ge ionization                                                           |
|                   | ANAIS      | 10 | $10 \times 10.7$ Kg NaI scintillators                                    |
|                   | ROSEBD     | 50 | g Al$_2$O$_3$ and 67 g Ge thermal detectors                               |
|                   |            |    | CaWO$_4$ 54g and BGO 40g scintillating bolometers                         |
| FREJUS/MOADANE (France) | SACLAY - NaI | 9.7| Kg NaI scintillator (recently completed)                                  |
|                   | EDELWEISS I| 70 | g Ge thermal + ionization detector                                        |
|                   | EDELWEISS II| 4 | x 320 g Ge thermal + ionization detectors                                |
| GRAN SASSO (Italy)| H/M        | 2.7| Kg Ge ionization                                                          |
|                   | HDMS       | 200| g Ge ionization in Ge well                                               |
|                   | GENUS-TF   | 40 | x 2.5 Kg Unencapsulated Ge (in preparation)                               |
|                   | DAMA       | NaI| scintillators (87.3 Kg)                                                 |
|                   | LIBRA      | NaI| scintillators (250 Kg (in preparation)                                   |
|                   | Liquid-Xe  | Li| Liquid Xe scintillator (6 Kg)                                            |
|                   | CaF$_2$    | Sc| Scintillator                                                              |
|                   | CRESSST I  | (4 | x 260 g) Al$_2$O$_3$ thermal detectors                                   |
|                   | CRESSST II | Set of 300 g CaWO$_4$ scintillating bolometers (up to 10 Kg)             |
|                   | MIBETA     | 20 | x 340 g TeO$_2$ thermal detector                                         |
|                   | CUORICINO   | 56| x 760 g TeO$_2$ thermal detector (being mounted)                        |
|                   | CUORE      | 1000 x 760 g TeO$_2$ (in preparation)                                   |
| RUSTREL (France)  | SIMPLE     | (SSD)| Superheated Droplets Detectors (Freon)                                  |
| STANFORD (USA)    | CDMX - I   | 100| g Si, 6 x 165 g Ge thermal + ionization detectors                         |
|                   | CDMX - II  | 3 | x 250 g Ge and 3 x 100 g Si Thermal + Ionization                          |
| SNO (Canada)      | PICASSO    | (SDD)| Superheated Droplets Detectors (1.54 g of Freon)                       |
| OTTO-GSMD (Japan) | ELEGANTS - V| Large set of massive NaI scintillators                                  |
|                   | ELEGANTS - VI | CaF$_2$ scintillators                                                  |

Table 4

References

[1] G. Jungman, M. Kamionkowski and K. Griest, Phys. Rep. 267 (1996) 195.
[2] A. Morales, “Dark Matter and its Detection”, Summary Talk given at the NUPECC Workshop on Present and Future of Neutrino Physics, Frascati, NUPECC Report in Highlights and Opportunities in Nuclear Physics, Ed. by J. Vervier et al., December 1997. (astro-ph/9810341).

[3] F.T. Avignone and A. Morales, Proc. Int. Conference on Neutrino Physics and Astrophysics. Helsinki, June 1996, ed. K. Enkvist et al. in World Scientific Pub. (1997) p. 413; A. Morales “Selected Projects in Direct Detection of Dark Matter”, Proc. Neutrino Telescopes Workshop, Venice, February 1999. Ed. M. Baldo-Ceolin, p. 24; L. Baudis and H.V. Klapdor ”Direct Detection of Non Baryonic Dark Matter”, astro-ph/0003434 and Y. Ramachers ”Non Baryonic Dark Matter Searches”; XI Rencontres de Blois, June 1999, astro-ph/9911260.

[4] A. Morales, “Direct Detection of WIMP Dark Matter” (astro-ph/9912554). 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, to be published in Nucl. Phys. B (Proc. Suppl.) 2002.

[5] Topics in Astroparticles and Underground Physics, TAUP 1999 Proceedings, Nucl. Phys B (Proc. Suppl.) 87 (2000), Edited by J.Dumanchez, M.Froissart and D.Vignaud.

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

[7] 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.

[8] J. Morales et al., Nucl. Instrum. & Meth. A321 (1992) 410.

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

[10] D.O. Caldwell et al., Phys. Rev. Lett. 61 (1988) 510.

[11] D. Reusser et al., Phys. Lett. B 255 (1991) 143.

[12] M. Beck et al., Phys. Lett. B 336 (1994) 141.

[13] R. Bernabei et al., Phys. Lett. B379 (1996) 299.

[14] C. Aalseth et al., Phys. Rev. C59 (1999) 2108.

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

[16] 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.

[17] J. Engel, Phys. Lett. B264 (1991) 114.

[18] L. Baudis et al., Phys. Rev. D59 (1999) 022001.

[19] R. Bernabei et al., Phys. Lett. B450 (1999) 448 and Phys. Lett. B480 (2000) 23.

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

[21] A. Morales et al. [IGEX Collaboration], hep-ex/0110061 oct. 2001 and I.G. Irastorza et al. (IGEX coll.), talk given at the TAUP Workshop Sept. 2001, LN Gran Sasso. To be published in Nucl. Phys. B (Proc. Suppl.) 2002.

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

[23] A. Benoit et al. [EDELWEISS Collaboration], Phys. Lett. B 513 (2001) 15 (astro-ph/0106094).
[24] B. Sadoulet, private communication to A. Morales and talk given at TAUP 2001 Workshop, LNGS (September 2001). To be published in Nucl. Phys. B (Proc. Suppl.) 2002.

[25] 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.

[26] S. Cebrian et al., Astropart. Phys. 14 (2001) 339.

[27] A.K. Drukier et al., Phys. Rev. D33 (1986) 3495.

[28] See Igor G. Irastorza. Thesis Disertation. Univ. of Zaragoza. April 2001.

[29] S. Cebrian, private communication.

[30] See for instance A. Bottino et al. DFTT 35/2000 and references therein; J. Ellis et al. [hep-ph/0007113] and P. Gondolo [hep-ph/0008022].