IMPROVED CONSTRAINTS ON WIMPS FROM THE INTERNATIONAL GERMANIUM EXPERIMENT IGEX

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Abstract

One IGEX $^{76}$Ge double-beta decay detector is currently operating in the Canfranc Underground Laboratory in a search for dark matter WIMPs, through the Ge nuclear recoil produced by the WIMP elastic scattering. A new exclusion plot, $\sigma(m)$, has been derived for WIMP-nucleon spin-independent interactions. To obtain this result, 40 days of data from the IGEX detector (energy threshold $E_{th} \sim 4$ keV), recently collected, have been analyzed. These data improve the exclusion limits derived from all the other ionization germanium detectors in the mass region from 20 GeV to 200 GeV, where a WIMP supposedly responsible for the annual modulation effect reported by the DAMA experiment would be located. The new IGEX exclusion contour enters, by the first time, the DAMA region by using only raw data, with no background discrimination, and excludes its upper left part. It is also shown that with a moderate improvement of the detector performances, the DAMA region could be fully explored.

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 prejudice is that the universe consists of unknown species of Dark Energy ($\Omega_\Lambda \sim 70\%$) and Dark Matter ($\Omega_M \sim 25 - 30\%$) of which less than $\sim 5\%$ is of baryonic origin. Most of that Dark Matter is supposed to 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.

WIMPs can be detected by measuring the nuclear recoil produced by their elastic scattering off target nuclei in a suitable detector\textsuperscript{[1]}. In particular, non-relativistic ($\sim 300$ km/s) and heavy ($10 - 10^3$ GeV) galactic halo WIMPs could make a Ge nucleus recoil with a few keV, at a rate which depends on the type of WIMP and interaction. Only about 1/4 of this energy is visible in the detector. Because of the low interaction rate (which ranges from 10 to $10^{-5}$ counts/kg/day according to the SUSY model and the choice of parameters) and the small energy deposition (from a few to $\sim 100$ keV), the direct

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search for particle dark matter through scattering off nuclear targets requires ultralow background detectors with very low energy thresholds.

Germanium detectors have reached one of the lowest background levels of any type of detector and have a reasonable ionization yield (nuclear recoil ionization efficiency relative to that of electrons of the same kinetic energy) ranging from 20% to 30% depending on the nuclear recoil energy. Thus, with sufficiently low energy thresholds, they are attractive devices for WIMP searches. That is the case for IGEX.

This paper presents new WIMPs constraints in the cross-section WIMP-nucleon versus WIMP mass plot, derived from a germanium detector (enriched up to 86% in $^{76}\text{Ge}$) of the IGEX collaboration, which improve previous limits obtained with Ge ionization detectors, and enter by the first time the so-called DAMA region (corresponding to a WIMP supposedly responsible for the annual modulation effect found in the DAMA experiment [2]) without using mechanisms of background rejection, but relying only in the ultra-low background achieved.

2 Experiment

The IGEX experiment [3, 4], optimized for detecting $^{76}\text{Ge}$ double-beta decay, has been described in detail elsewhere. One of the IGEX detectors of 2.2 kg, enriched up to 86% in $^{76}\text{Ge}$, is being used to look for WIMPs interacting coherently with the germanium nuclei. Its active mass is $\sim 2.0$ kg, measured with a collimated source of $^{152}\text{Eu}$. The full-width at half-maximum (FWHM) energy resolution is 2.37 keV at the 1333 keV line of $^{60}\text{Co}$. Energy calibration and resolution measurements were made periodically using the lines of $^{22}\text{Na}$ and $^{60}\text{Co}$. Calibration for the low energy region was extrapolated using the X-ray lines of Pb. The uncertainty induced by this extrapolation in the determination of the energy values in the threshold region has been estimated to be smaller than 0.1 keV, as deduced from the check of linearity performed systematically—with this and other detectors of IGEX—along several years since the arrival of the detector to the underground facility, when the activation peaks (at about 10 keV) were still visible.

The Ge detector and its cryostat were fabricated following state-of-the-art ultralow background techniques and using only selected radiopure material components (see Ref. [3, 5]). The first-stage field-effect transistor (FET) of the detector 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 the background. Further stages of preamplification are located at the back of the cryostat cross arm, approximately 70 cm from the crystal. The IGEX detectors have preamplifiers modified for the pulse-shape analysis used in the double-beta decay searches.

The detector shielding has been recently modified with respect to that of the previous set-up of Ref. [3], improving the external neutron shielding and increasing the thickness of lead surrounding the detector. The shielding is now as follows: the innermost shield consists of about 2.5 tons of 2000-year-old archaeological lead of ancient Roman origin (having < 9 mBq/kg of $^{210}\text{Pb}$, $^{210}\text{Bi}$), < 0.2 mBq/kg of $^{238}\text{U}$, and < 0.3 mBq/kg of $^{232}\text{Th}$) forming a cubic block of 60 cm side. The detector is fitted into a precision-machined chamber made in this central core, which minimizes the empty space around the detector available to radon. Nitrogen gas, at a rate of 140 l/hour, evaporating from liquid nitrogen, is forced into the small space left in the detector chamber to create a positive pressure and further minimize radon intrusion. The archaeological lead block is surrounded, at its turn, by 20 cms of lead bricks made from 70-year-old low-activity lead (~ 10 tons) having ~ 30 Bq/kg of $^{210}\text{Pb}$. The whole lead shielding forms a 1-m cube, the detector being surrounded by not less than 40-45 cm of lead (25 cm of which is archaeological). 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 shield, except where the detector Dewar is located. The veto consists of BICRON BC-408 plastic scintillators 5.08 cm × 50.8 cm × 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 with a count rate lesser than 40 Hz (i.e., using a threshold which allows to include events with a poor light collection). An external neutron moderator 40 cm thick formed by
polyethylene bricks and borated water tanks completes the shield. The entire shield is supported by an iron structure resting on noise-isolation blocks. The experiment has an overburden of 2450 m.w.e., which reduces the muon flux to a (measured) value of $2 \times 10^{-7}$ cm$^{-2}$s$^{-1}$.

The data acquisition system for the low-energy region used in this WIMP search is based on standard NIM electronics. It has been implemented by splitting the normal preamplifier output pulses of the detector and routing them through two Canberra 2020 amplifiers having different shaping times enabling noise rejection as first applied in Ref. [3]. The minimum settled ratio of the two amplitudes processed with different shaping time depends on the energy and in the present case it ranges from 0.8 (at 4 keV) to 0.99 (at 50 keV). 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. Figure 1 shows the time-after-last-veto distribution of the events. Notice that it reflects properly the 200 µs delay included in the main trigger of the acquisition system for the computer to decide whether it acquires or not the digitized pulse after knowing its energy. The muon veto anticoincidence was done off-line with a software window up to 240µs. The probability of rejecting non-coinicident events is less than 0.01.

The rejected veto-coinicident events amount up to about the 5% of the total rate and are distributed in the low energy region as shown by the Figure 2.

In addition, the pulse shapes of each event before and after amplification are recorded by two 800 MHz LeCroy 9362 digital scopes. These are analyzed one by one by means of a method based on wavelet techniques which allows us to assess the probability of this pulse to have been produced by a random fluctuation of the baseline. The method requires the calculation of the wavelet transform of $f(x)$, the recorded pulse shape after amplification:

$$[W_{\psi}f](a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} f(x) \psi \left( \frac{x-b}{a} \right) dx$$  \hspace{1cm} (1)

where the ”mexican hat” wavelet function $\psi(x) \propto (1-x^2) \exp \left(-\frac{1}{2}x^2\right)$ was chosen for our purposes. Following expression (1), a two-parameter function $[W_{\psi}f](a,b)$ was numerically obtained for each event. The relative maxima of this function were calculated, the highest one corresponding to the event pulse and the others to random fluctuations of the baseline. It was proven that the distribution of the values of the wavelet transform at these points follows an exponential. By comparing the maximum corresponding to the event pulse with this exponential one can calculate the probability $P$ for the first maximum to belong to the distribution of the other maxima. This value is the final output of the analysis for each event and is interpreted as the probability of the main pulse of being randomly generated by the fluctuations of the baseline.

In order to fix the rejection criterion this method was applied to a calibration set of data. The result is shown in Figure 3 where the probability obtained with this method versus energy is presented for each event. The same plot but for a background set of data is shown in Figure 4. From these plots a criterion of $P < 0.01$ can be defined to distinguish the two populations of noise and data. Although it is hard to quantify the loss of efficiency with the available statistics, the figures show that it is very small for events above 4 keV.

It is worth mentioning that in spite of its good efficiency, this technique was not able, by itself alone, to improve the previous low energy background presented in Ref. [3]. Therefore, we concluded that noise and microphonics does not contribute substantially to such background and, consequently, the reduction of background presented in the next section is attributed to the changes in the shielding.

### 3 Results and prospects

The results presented in this paper are from a recent run with the modified shielding and analysis system previously described. They correspond to an exposure of $M_t=80$ kg days. The spectrum obtained is shown in Figure 5 compared with the previous IGEX published spectrum of Ref. [4]. The numerical data are also given in Table 1. The high energy region up to 3 MeV is shown in Figure 6.

The energy threshold of the detector is 4 keV and the FWHM energy resolution at the 75 keV Pb X-ray line was of 800 eV. The background rate recorded was $\sim 0.21$ c/keV/kg/day between 4–10 keV, $\sim 0.10$ c/keV/kg/day between 10–20 keV, and $\sim 0.04$ 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 (5), essentially due to the improved shielding (both in lead and in polyethylene-water). As was stressed before, this reduction was not due to the implementation of the Pulse Shape Analysis, which suggests that the neutrons could be an important component of the low energy background in IGEX.

The exclusion plots are derived from the recorded spectrum in one-keV bins from 4 keV to 50 keV, by requiring the predicted signal in an energy bin 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 \( \rho = 0.3 \text{ GeV/cm}^3 \), have a Maxwellian velocity distribution with \( v_{\text{rms}} = 270 \text{ km/s} \) (with an upper cut corresponding to an escape velocity of 650 km/s), and have a relative Earth-halo velocity of \( v_e = 230 \text{ km/s} \). The cross sections are normalized to the nucleon, assuming a dominant scalar interaction. The Helm parameterization (7) is used for the scalar nucleon form factor. To compare the IGEX exclusion plots with that derived from the Heidelberg-Moscow data (8), the recoil energy dependent ionization yield used is the same that in Ref. (8), \( E_{\text{vis}} = 0.14 (E_{\text{recoil}})^{1.19} \).

The exclusion plot derived in this way is shown in Fig. 3 (thick solid line). It improves the IGEX-DM previous result (thick dashed line) as well as that of the other previous germanium ionization experiments (including the last result of Heidelberg-Moscow experiment (8) –thick dotted line–) for a mass range from 20 GeV to 200 GeV, which encompass that of the DAMA mass region. In particular, this new IGEX result excludes WIMP-nucleon cross-sections above \( 7 \times 10^{-9} \text{ nb} \) for masses of \( \sim 50 \text{ GeV} \) and enters the so-called DAMA region where the DAMA experiment assigns a WIMP candidate to their found annual modulation signal. 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 (9) and EDELWEISS (10) (thin dashed line), which have entered that region, as well as the DAMA region (closed line) corresponding to the 3\( \sigma \) annual modulation effect reported by that experiment (11) and the exclusion plot obtained by DAMA NaI-0 (thin solid line) (12) by using statistical pulse shape discrimination. A remark is in order: for CDMS two contour lines have been depicted according to a recent recommendation (12), the exclusion plot published in Ref. (12) (thin dotted line) and the CDMS expected sensitivity contour (12) (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), that region would be widely surpassed. In Figure 3 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 (\( m=52^{+10}_{-8} \text{ GeV}, \sigma_p=(7.2^{+0.4}_{-0.9}) \times 10^{-9} \text{ nb} \)) could be tested with a moderate improvement of the IGEX performances.

A new experimental project on WIMP detection using larger masses of Germanium of natural isotopic abundance (GEDEON, GERmanium DEtectors in ONe cryostat) is planned. It will use the technology developed for the IGEX experiment and it would consist of a set of \( \sim 1 \text{ kg} \) 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. A detailed study is in progress to assess the physics potential of this device, but it can be anticipated that a flat background of 0.002 c/kg/keV/day down to a threshold below 4 keV is a reasonable estimate. The exclusion plot which could be expected with such proviso for 24 kg y of exposure is shown in the Figure 4. Moreover, following the calculations presented in (13), GEDEON would be massive enough to search for the WIMP annual modulation effect and explore positively an important part of the WIMP parameter space including the DAMA region.

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Figure 1: Distribution of the time after last veto event. The distribution is centered at \( \sim 200\mu s \) as expected (see text).
Figure 2: Distribution at low energies of the events rejected by the veto system.
Figure 3: Scatter plot of the probability assigned to each event by the wavelet technique (described in the text) versus energy for a calibration set of data.
Figure 4: Same as Figure 3 but for background data. The populations of noise and data are well separated above 4 keV.
| 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       |

Table 1: Low-energy data from the IGEX RG-II detector (Mt = 80 kg d).
Figure 5: Normalized low energy spectrum of the IGEX RG-II detector corresponding to the 80 kg d presented in this paper (thick line) compared to the previous 60 kg d spectrum published in [5].
Figure 6: High energy region of the spectrum of the IGEX RG-II detector corresponding to the 80 kg data presented in this paper.
Figure 7: IGEX-DM exclusion plot for spin-independent interaction obtained in this work (thick solid line) compared with the previous exclusion obtained by IGEX-DM \[\text{[5]}\] (dashed thick line) and the last result obtained by the Heidelberg-Moscow germanium experiment \[\text{[8]}\] (dotted line) recalculated from the original spectrum with the same set of hypothesis and parameters. The closed line corresponds to the (3\(\sigma\)) annual modulation effect reported by the DAMA collaboration (including NaI-1,2,3,4 runnings) \[\text{[2]}\]. The thin solid line is the exclusion line obtained by DAMA NaI-0 \[\text{[11]}\] by using Pulse Shape Discrimination. The two other experiments which have entered the DAMA region are also shown: EDELWEISS \[\text{[10]}\] (thin dashed line) and the CDMS exclusion contour (thin dotted line) \[\text{[9]}\] and its expected sensitivity \[\text{[12]}\] (thin dot-dashed line).
Figure 8: 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.