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Low-mass WIMP searches with the EDELWEISS experiment

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Abstract. The EDELWEISS experiment is a direct search for Weakly Interacting Massive Particles (WIMP) dark matter using an array of twenty-four 860 g cryogenic germanium detectors equipped with a full charge and thermal signal readout. The experiment is located in the ultra-low radioactivity environment of the Modane underground laboratory in the Frejus tunnel. WIMP limits, background rejection factors and measurements of cosmogenic activation recorded in long exposures are used to assess the performance of the third generation of EDELWEISS detectors in view of the search for WIMPs in the mass range from 1 to 20 GeV/c^2. The developments in progress to pursue this goal in the coming years are also presented.

1. The EDELWEISS experiment

The EDELWEISS experiment [1] uses cryogenic germanium detectors to perform a direct search for Weakly Interacting Massive Particles (WIMPs) [2]. The scattering of these particles – present in our galactic halo – on germanium nuclei should produce nuclear recoils with kinetic energy in the tens of keV range. The radioactive background must be kept at extremely low values in order to be sensitive to this elusive signal. For this reason, the detectors are operated in a radiopure underground environment located in the Laboratoire Souterrain de Modane (LSM) where the 4800 meter-water-equivalent rock cover reduces the cosmic-ray flux to 5 μ·m^{-2}day^{-1}. An additional shielding of 50 cm of polyethylene and 20 cm of lead surrounds the detector setup and a 100-m^2 plastic scintillator muon veto [3] tags residual muons that could produce neutrons (mostly in the lead shielding). In its EDELWEISS-III configuration, described in Ref. [1], the detector array consists of twenty-four germanium crystals of masses between 820 and 890 g (the so-called FID detectors). A dilution refrigerator cools down the array at a temperature of 18 mK. Parts of the lead and polyethylene shields are cooled down at a temperature below 2 K. Each detector is equipped with an event-by-event readout of two signals: the total deposited energy (calorimetric measurement) and the ionization yield. The combination of the two enables the separation of the electron recoils (that constitute the dominant background) from the sought-for nuclear recoils using the difference of a factor of approximately three in the ionization yields of these two types of events. The $\sim \mu$K elevation of temperature associated to each event is measured with a pair of Ge-NTD heat sensors glued to each of the two flat surfaces of the cylindrical crystal. The ionization signal is collected on interleaved ring electrodes [4] separated by $\sim$2 mm and covering all surfaces, including the cylindrical one. The electrode scheme is

[1] http://edelweiss.in2p3.fr/Collaboration/list.php

designed for the tagging of electron recoils occurring close to the surface of the detector, a population that can be affected by reduced ionization yields [4] and thus can mimic nuclear recoils. The rings of the top (bottom) half of the detector are alternatively biased at +4V and -1.5V (-4V and +1.5V). Electron-hole pairs created $<\sim 2$ mm below the surface are collected by the so-called *fiducial* electrodes (±4V) on each side of the detector, while events close to the surface leave part of their signals on *veto* electrodes (±1.5V) on either side of the detector.

2. EDELWEISS-III performance

The performance of the FID detectors have been measured using large-statistics calibrations [1]. The position of the nuclear recoil band, corresponding to an acceptance of 90% for all nuclear recoils, has been determined down to a recoil energy of 2.5 keV using more than 3×10^4 events recorded with an AmBe source. The fraction of the volume of each detector corresponding to fiducial events has been measured using the intensity of the triplet at 8.98, 9.67 and 10.36 keV associated to the decay of ^{65}Zn, ^{68}Ga and ^{68}Ge nuclei produced by cosmogenic activation in the entire volume of the detectors before they were brought underground. The intensities of these peaks, as well as those of the activation lines of ^{49}V, ^{54}Mn and ^{55}Fe and of the β-spectra of ^{3}H, have also been measured and interpreted in terms of the production rates of these isotopes via the cosmic activation of germanium [5]. The tritium result is the first precise measurement of this kind and described in more details in another talk at this conference [6]. The rejection of electron recoils in the fiducial volume has been measured with a total of 9.38×10^5 γ rays from a ^{133}Ba source, setting a 90%C.L. upper limit of 2.5×10^{-6} for the fraction of events leaking into the nuclear recoil band. The most important source of events with a deficit in ionization yield comes from the decay of ^{210}Pb and its daughters, present at contaminant levels on the surfaces of the detector and the material in the immediate surroundings. The ability of the interleaved electrode scheme to reject the electron recoils from ^{210}Pb and ^{210}Bi decays, as well as ^{206}Pb and α particle recoils from ^{210}Po decays, has been measured by covering all surfaces of two detector casings with copper adhesive strips previously exposed to radon. The measured 90%C.L. upper limit on the combined rejection factor for all these surface events is 4×10^{-5}.

3. EDELWEISS-III low-mass WIMP search results

Finally, a WIMP search was performed based on a data set corresponding to 161 days of physics, for a total exposure of approximately 3000 kg·day. All twenty-four detectors were used to reject coincidences, reducing the γ-ray background by a factor two. The low-energy data of eight of the detectors with the lowest energy threshold were used to search for WIMPs with masses between 4 and 30 GeV/c^2 [7, 8]. The backgrounds were modeled using sideband data as much as possible. For instance, the sideband for fiducial electron recoils are events with ionization yields greater than 0.5, and the sideband for interactions from radioactive contaminants at the surface of the detector are events with signals on veto electrodes that are significant by more than 5σ. These populations are extrapolated into the region of WIMP search using the measured experimental resolutions. An important background was that from the so-called heat-only events (HO). These are characterized by having an ionization signal consistent with zero. They are single events and their pulse shapes cannot be distinguished from normal bulk events. Their rate and energy spectrum (shown in figure 1) is taken from events with negative ionization signals, mirrored into the WIMP search region limited to positive ionization signals. Single-hit events generated by the scattering of neutrons from radiogenic origins[2] cannot be distinguished from WIMP scattering events. Their energy spectrum is obtained from Monte-Carlo simulations and their rate is taken as the one measured for multiple-hit nuclear recoil events multiplied by the single-to-multiple

[2] Due to the large efficiency to tag muon-induced neutrons by the presence of a signal within 10 ms, the number of single-hit nuclear recoil from this source is estimated to be < 0.04 at 90%C.L.

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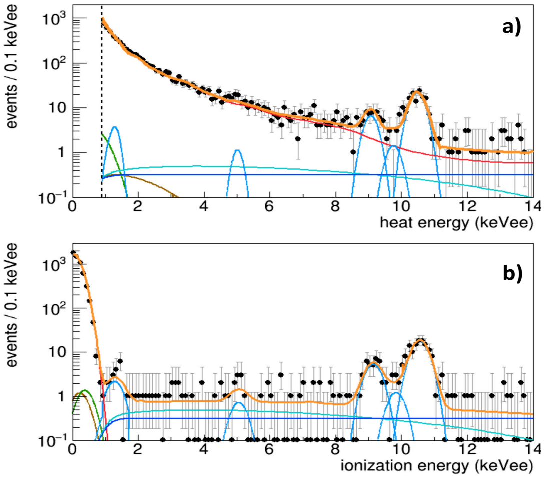

Figure 1. Energy spectra in the heat (a) and ionization (b) energies for the WIMP search data (see text) for the detector FID824. The orange line is the best fit from the likelihood fit with a mass of 4 GeV/c^2, dominated by the HO events in red. See Ref. [8] for the description of the other lines.

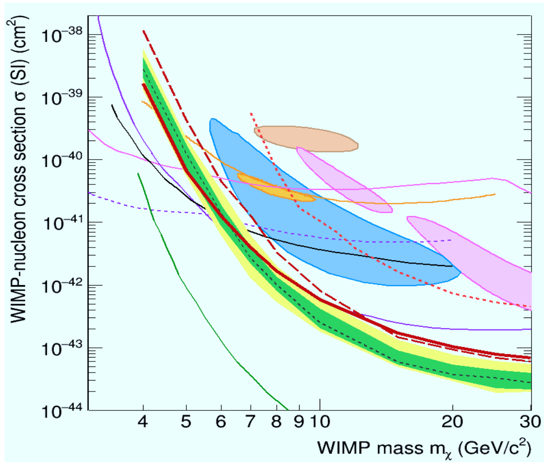

Figure 2. Calculated 90% C.L. exclusion limit on the spin-independent WIMP-nucleon scattering cross section as a function of WIMP mass obtained by the EDELWEISS likelihood [8] (solid red) and BDT [7] analyses. See Ref. [8] for the description of the other lines.

hit ratio of the simulations. This is the only background modeled partly using Monte Carlo simulation and not entirely using sideband data, and a large systematic error is ascribed to its evaluation. These background models were used in two analyses aimed at evaluating the 90% C.L. exclusion limit on the spin-independent WIMP-nucleon scattering cross section as a function of WIMP mass. In the first analysis these models were used to train a Boosted Decision Tree (BDT) [7]. More recently [8], they were used to define Probability Density Functions for the different backgrounds as a function of the heat and fiducial ionization signals to perform a 2D profile likelihood analysis. The 90% C.L. limits derived by the two analyses are shown in figure 2. For WIMP masses above 15 GeV/c^2, the results are similar, as expected as the sensitivity is limited by the irreducible background of neutron-induced single-hit events. Below, the effect of the HO background dominates. For a WIMP mass of 4 GeV/c^2 the likelihood analysis results are a factor seven more stringent than those of the BDT analysis. This is an improvement by more than two orders of magnitude relative to the EDEWEISS-II results [9] for a mass of 7 GeV/c^2.

4. Prospects

Improving the sensitivity for low-mass WIMPs requires significant improvements of the experimental thresholds. As presented in Ref. [10], this is achievable by working on the four following points: Firstly, the heat signal can be amplified by the Luke-Neganov effect [11]. This corresponds to the additional heating associated to the work performed to drift the electrons and holes in the electric field applied to the detector. The thermal heat signal is amplified by a factor $(1+V/\epsilon)$, where V is the applied bias and ϵ is the average incident energy needed to create an electron-hole pair in germanium, *i.e.* 3 eV for an electron recoil interaction, and close to 12 eV for a nuclear recoil. It has been measured in γ-ray calibrations that increasing the bias of the

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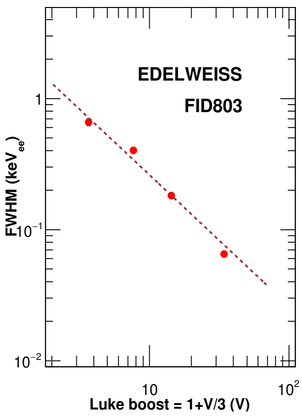

Figure 3. Heat energy resolution in keV$_{ee}$ as a function of the applied voltage for the detector FID803.

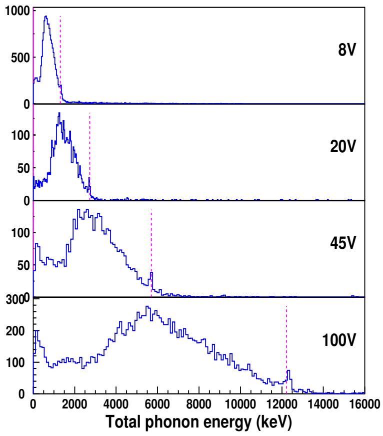

Figure 4. Total heat energy spectra recorded with a ^{133}Ba source at the biases of figure 3. The red lines are the expected position for the 356 keV γ ray.

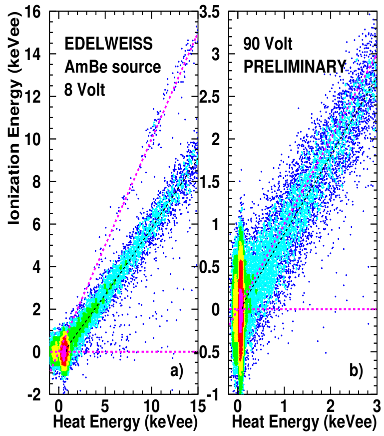

Figure 5. Ionization energy versus heat energy, both in keV$_{ee}$, recorded with an AmBe neutron source at 8V (a) and 90V (b) with FID803.

FID detectors from 8 to 100 V improves the heat resolution in units of keV-equivalent-electron (keV$_{ee}$) by the expected factor 103/11 (figure 3). This corresponds to the expected increase of the total energy (sum of the recoil energy and Luke-Neganov heating) as a function of V, with a proportionality factor of $1{+}V/\epsilon$ (figure 4), while the resolution on the thermal measurement remains the same. Once the signal is converted in units of keV$_{ee}$ (*i.e.* normalized to the expected energy in the case of an electron recoil event), the resulting resolutions shown in figure 3 decrease with V. The baseline resolution of the heat signal, and therefore the trigger threshold, can thus be reduced to increase the efficiency to low-mass WIMPs. As shown in figures 3 and 4, it has already been possible to increase the bias applied to the EDELWEISS detectors from 8 of 100 V. However, at high bias the Luke energy dominates the total heat energy and the heat signal becomes a simple copy of the ionization signal, albeit with an improved resolution. This means that the separation between nuclear and electron recoils can no longer be used to efficiently reject the later (figure 5). However, for searches for WIMPs with masses below 4 GeV/c^2, this effect is largely compensated by the improvement in efficiency [10]. Secondly, detailed studies and modeling have shown evidence for a sensitivity to ballistic phonons and a parasitic heat capacity that had not been suspected before, revealing the possibility to improve the resolution on the heat signals by a factor five. Thirdly, the studies in Ref. [10] indicate that sensitivity to WIMP cross sections down to 10^{-41} cm^2 are achievable even with the present-day rates of HO events. The possible origin of these events is nevertheless being investigated, such as noise, cryogenics, stress from detector suspension or gluing. These investigations have so far led to the development and the test of new types of sensors such as deported NTDs, glued on separate sapphire wafers, or photo-lithographed high impedance NbSi Transition Edge Sensors, sensitive to athermal phonons. These three developments are pursued in the context of EDELWEISS-LT (Low Threshold), with the objective to operate four Luke-boosted 800 g detectors in the current EDELWEISS environment to reach sensitivities of 10^{-41} cm^2 for WIMP masses between 1 and 10 GeV/c^2 [10]. It has been recently shown that High Electron Mobility Transistors (HEMTs) cooled-down at 4 K could be used as pre-amplifier and result in a $\sigma = 91$ eV$_{ee}$ resolution on the charge signal for a SuperCDMS detector with a capacitance of 130 pF [12]. FID detectors offer the possibility to further reduce the detector capacitance. For example, one FID with an inter-electrode spacing of 4 mm instead of 2 mm had been successfully used in the previously discussed WIMP search. Reducing the ionization resolution to 50 eV_{ee} opens the possibility to retain the very efficient separation of nuclear and electron recoils down to 1 keV and to have a resolution on the energy scale of 10% at that energy. Such performance would pave the way for a detailed measurement of the important, and yet to be observed, signal from nuclear recoils from the coherent scattering of solar neutrinos from ^{8}B decays, that are an almost irreducible background for the search of WIMP with masses close to 6 GeV/c^2. This program, labelled EDELWEISS-DMB8, would require a $\sim$200 kg scale array operated in an appropriate reduced-background environment [10] such as the one planned for the SuperCDMS-SNOLAB experiment.

5. Conclusion

The EDELWEISS experiment, in its third stage, has vastly improved its sensitivity to WIMP with masses between 4 and 30 GeV/c^2. The EDELWEISS-LT program aims to improve the experimental thresholds by a factor ten using notably the Luke-Neganov boost of the thermal signal. Biases of 100V have been already achieved on 800 g detectors. Sensitivities to cross sections down to 10^{-41} cm^2 are achievable with four detectors operated with present levels of backgrounds. At longer term, an ionization resolution of 50 eV_{ee} obtained using HEMT preamplifiers opens the possibility to observe a clear spectral identification of nuclear recoils originating form the coherent scattering of solar neutrinos from ^{8}B decays in the framework of the EDELWEISS-DMB8 program.

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