Searching for WIMPs with EDELWEISS

Eric Armengaud, for the EDELWEISS collaboration
IRFU/SPP, CEA Saclay, 91191 Gif-sur-Yvette, France
E-mail: eric.armengaud@cea.fr

Abstract. The EDELWEISS-II experiment, operated in the Frejus laboratory in a low-background environment, uses cryogenic germanium detectors to look for WIMPs. We present the results of a WIMP search carried out recently with ten so-called InterDigit detectors. This technology enables a high level of gamma radioactivity rejection within a controlled fiducial volume. A cross-section of $4.4 \times 10^{-8}$ pb could be excluded for a WIMP mass of 85 GeV. We also present the status of the EDELWEISS-III project, which will operate 40 newly-designed FID detectors in an upgraded installation to improve significantly the sensitivity to low WIMP scattering cross-sections.

1. Introduction

The nature of what is perceived as dark matter from cosmological and astrophysical observations remains totally unknown. A large experimental effort is currently devoted to test the WIMP hypothesis: dark matter would be constituted of weakly interacting particles with GeV-TeV scale mass, associated to new physics at the electroweak scale which may be probed at colliders like LHC. The best way to test this hypothesis is to achieve the direct detection of WIMPs from our galactic halo, by measuring the nuclear recoil spectrum generated by their interactions in a detector. The interaction rates are less than an event per kg per day, and the recoil energies are at some tens of keV. Dedicated detectors must therefore achieve a low energy threshold combined with high background rejection capabilities.

The EDELWEISS collaboration [1] designs germanium bolometers with a dual heat-and-ionization readout to reach this goal. In the following, we will present the EDELWEISS-II infrastructure and detectors whose novelty rely on the ability to reject surface interaction with an interleaved electrode design. We then review the results of a WIMP search which was recently published in [2], as well as a combination of this search with a similar one by the CDMS collaboration [3]. Finally, we present the status of the currently ongoing EDELWEISS-III program.

2. Experimental setup and detector performances

2.1. The EDELWEISS-II installation at Modane

EDELWEISS-II consists of a dilution cryostat able to host up to 40 kilograms of target material down to 18 mK. Its reversed geometry simplifies the installation of detectors. The whole cryogenic system can be remotely controlled, and operated this way during months without major trouble.

The experiment is located in the Modane Underground Laboratory (LSM), with a 4800 m water-equivalent depth reducing the cosmic muon flux down to $\sim 4\mu/m^2/day$. To reduce
environmental backgrounds, all materials used in the vicinity of the detectors were tested for their radiopurity with dedicated HPGe detectors. A clean room surrounds the whole setup, and the cryostat environment is under a permanent flow of deradonized air. A 20 cm thick lead shield around the cryostat screens the external gamma background. Fast neutrons generate nuclear recoils that cannot be discriminated against WIMPs when occurring as single-hit events. To protect detectors against neutrons, a 50 cm thick polyethylene shielding attenuates this background by three orders of magnitude. Furthermore a muon veto with a coverage of more than 98% tags neutrons produced by muons within this PE shield, in particular in the lead shield.

2.2. The InterDigit detector principle

EDELWEISS-II detectors are Germanium bolometers of typical mass $\sim 400$ g, with electrodes deposited on their surfaces. At around 20 mK operating temperature, low energy interactions are detected by neutron transmutation doped (NTD) heat sensors that are glued at the surface of the crystals. A measurement of the ionization yield is provided by the additional electrode signals for each interaction. Since electron recoils yield a factor $\sim 3$ times more ionization signal than nuclear recoils, an event-by-event discrimination against the gamma background is therefore possible with a high rejection power.

However, this rejection is possible only when the charges generated by an interaction are well collected, which is not always the case for interactions taking place near the electrodes. In particular, beta radioactivity from nearby surfaces, or from the detector surfaces themselves, would generate such a low-energy background. One therefore needs to be able to define a clean inner fiducial volume for each detector. For the InterDigit (ID) detector design, the electrodes used are concentric rings polarized at alternate voltages, as shown on Fig. 1. The resulting geometry of the electric field alters the propagation of charges near the surfaces: surface...
interactions are tagged by the presence of charge signals on the so-called veto electrodes located at the surface where the interaction takes place. On the other hand, interactions taking place within the fiducial volume generate an equal amount of charge on the two “collecting” electrodes on both sides of the crystal. The resulting discrimination against near-surface interactions is remarkably efficient, in particular because even when an interaction takes place in low electric field regions or just under collecting electrodes, the initial expansion of the charge cloud due to Coulomb interactions is sufficient to generate charges in a veto electrode. In first-generation ID detectors, the interleaved electrodes cover the top and bottom surfaces of the detectors. The cylindrical edge of the crystals are equipped with plain guard electrodes.

The first ID detector was built in 2007, and a few detectors were extensively tested at LSM in 2008. Physics runs were then carried out with 10 detectors in 2009-2010.

2.3. Measurements of detector performances
The ability to reject known sources of background against the fiducial nuclear recoils from WIMPs was tested on ID detectors using different radioactive sources.

The exposure of a 200-g ID detector to a $^{210}$Pb source provides a clean measurement of the low-energy beta background rejection factor. Fiducial interactions are selected by requiring both a perfect charge balance between the signals of the top and bottom collecting electrodes, and the absence of charge deposits on the field shaping (veto) and guard electrodes. This dual rejection provides a strong redundancy, and enables the detector operation even when charges cannot be read on one of the field shaping electrodes. A discrimination at a level of $\sim 10^{-5}$ was experimentally proven in [4].

Fig. 2 shows the measured ionization yield $Q$ as a function of recoil energy $E_{\text{rec}}$ for fiducial volume events observed during calibrations with a neutron source. The distributions for nuclear recoils (NR) were measured for each detector and were all found to be compatible with the parametrization $Q = 0.16 E_{\text{rec}}^{0.18}$ from less that 10 keV to 200 keV. The region with 90 % acceptance (1.64σ) for NR is well described by a parametrization using the experimental resolutions on the heat and ionization signals. Data from neutron calibrations also enables to test the influence of thresholds on the nuclear recoil efficiency. In particular, Fig. 2 illustrates the full efficiency of the detectors to NR even below 20 keV.

Regular gamma-ray calibrations with external $^{133}$Ba sources were carried out during the physics runs, and provided a total statistics of $3.5 \times 10^5$ electron recoils in the fiducial volume of the exposed detectors. Fig. 3 displays the measured ionization yield for these events, together with the average 90 % NR region. While the vast majority of electron recoils have an ionization yield far away from the NR region, a small population of “anomalous events”, namely 6 events, leaks down in the NR band. We derive a gamma rejection factor of $(3 \pm 1) \times 10^{-5}$ for these detectors in the recoil energy range $20 < E_{\text{rec}} < 200$ keV. It is suspected, but not fully proven yet, that these events are in fact due to multiple scatterings, with one interaction in the fiducial region and one in the guard region of the detectors, the latter having a less efficient charge collection.

Finally, the effective detector mass after fiducial selection was measured using low-background data itself: the cosmogenic isotopes $^{68}$Ge and $^{65}$Zn provide gamma-ray interactions homogeneously distributed within each crystal with an energy of $\sim 10$ keV. The ratio of event counts before and after the fiducial selection cuts provides a measurement of this cut efficiency in real WIMP search conditions. The average fiducial mass is 160 g. Electrostatic models confirm this value, and demonstrate that it is primarily limited by the presence of guard regions. Neutron calibrations also provided a consistency check for this measurement.
Figure 2. Ionization yield measurement as a function of recoil energy from neutron calibrations using all ID detectors used for WIMP search. The dotted lines represent the expected locations of gamma interactions (yield equal to one) and inelastic neutron scatterings (curved lines). The solid lines are the 90% elastic nuclear recoil parametrization.

Figure 3. Ionization yield measurement as a function of recoil energy from a large-statistics gamma-ray calibration with all ID detectors used for WIMP search. Red line: average NR band. Green line: average ionization threshold.
3. A search for WIMPs with ten ID detectors

3.1. Data set and backgrounds

A WIMP search was carried out between April 2009 and May 2010 with ten 400-g detectors. While all heat sensors were working correctly, a few veto or guard electrodes were malfunctioning (5 over 60 ionization channels), but the redundancy between channels prevented the loss of detectors for physics. The EDELWEISS-II setup provided a remarkably stable cryogenic environment at 18 mK during all this run. For each detector, an online trigger was applied on the heat sensor timelines. The recorded pulses are then processed offline using optimal filters. The rejection of noisy periods is carried out using the measured FWHM baselines, and requiring them to be below 2 keV for fiducial ionization and 2.5 keV for heat and guard ionization. These cuts imply a 17% exposure loss. The WIMP search cuts are then simply: fiducial volume selection; coincidence rejection (coincidences between detectors as well as with the muon veto); and finally selection of recoil energies between 20 and 200 keV, and ionization yields within the 90% NR region and outside the 99.99% gamma region. This results in a 384 kg.days net exposure.

The expected backgrounds are gamma and beta radioactivities, and fast neutron interactions.

- The measured gamma rejection factor described above, combined with the observation of 18000 bulk electron recoils during WIMP search, gives an expected background of < 0.9 events (90% CL).
- Similarly, the measured beta rejection factor is combined with the observation of 5000 surface events in WIMP search to give an expected background of < 0.3 events.
- A detailed description of the different sources of neutrons is given in other presentations of this conference [5, 6]. The observed muon-induced event rate combined with the muon veto efficiency gives an upper limit of 0.4 muon-induced neutron events. The measured neutron flux from the rock, and upper limits from radioactivity measurements of the lead, polyethylene and EDELWEISS infrastructure materials are combined to Monte-Carlo simulations to give an upper limit of 0.3 neutron events from these sources. A potentially more important neutron source had been identified as the connectors and cables located inside the cryostat, which could induce up to 1.1 nuclear recoil events.

Summing all these background upper limits gives an estimation of 3.0 background events in the NR region for the WIMP search.

3.2. Constraints on WIMP interactions

The observed distribution shows five events in the WIMP-search region (Fig. 4), one at 172 keV and the other ones between 20 and 23.2 keV. Given the abovementioned backgrounds, there is no clear evidence for WIMPs.

Applying the standard procedure in the field to set an upper limit in the presence of a weak, poorly constrained background [7], we obtain a limit on the spin-independent WIMP-nucleon cross-section of $4.4 \times 10^{-8}$ pb for a WIMP mass of 85 GeV. The 90% limit as a function of WIMP mass is presented on Fig. 5. This limit is degraded by the presence of the observed events at low energy.

The same data and analysis can be used to constrain a possible inelastic diffusion cross-section of WIMPs on nucleons. This scenario was invoked to reconcile the DAMA signal with other experiments, since in that case the expected recoil spectrum is globally reduced and suppressed at low recoil energies, and the modulation signal is enhanced. For example, if the WIMP excitation energy is 120 keV, the EDELWEISS data excludes the DAMA region for all WIMP masses above $\sim 90$ GeV.
Figure 4. Ionization yield versus recoil energy for the fiducial events recorded during the EDELWEISS-II WIMP search. The five candidates in the WIMP search band (red) are highlighted in red. Blue lines: 99.99% gamma discrimination line in average (continuous) or worst noise conditions (dashed). Green lines: ionization threshold in average (continuous) or worst noise conditions (dashed).

Figure 5. Limit at 90% CL on the WIMP-nucleon cross-section as a function of WIMP mass, obtained by the EDELWEISS-II search. Limits from other experiments, and a pre-LHC prediction in the CMSSM framework are also represented.
3.3. Combination with CDMS dataset

The EDELWEISS and CDMS collaborations have achieved similar sensitivities in WIMP search. In addition, the use of the same target material allows a simple combination of data. A common analysis between both collaboration was carried out in [3].

Though other methods have also been tested, a simple merger of datasets was chosen prior to analysis. The exposures of EDELWEISS (384 kg.d between 20 and 200 keV) and CDMS (∼379 kg.d between ∼10 and 100 keV, see [8]) were added, as well as the observed WIMP candidate events (5 events for EDELWEISS and 4 for CDMS). Applying the optimal interval method [7] to set an upper limit to the WIMP-nucleon cross-section, the obtained sensitivity, shown on Fig. 6, represents a ∼50% gain with respect to CDMS for large WIMP masses. There is no gain for WIMP masses below 50 GeV due to the threshold and the presence of events at low energy in the EDELWEISS dataset.

4. Status of the EDELWEISS-III project

The EDELWEISS-III project consists in an upgrade of both the current EDELWEISS setup and detectors in order to reach a sensitivity to the WIMP-nucleon cross-section of the order of $5 \times 10^{-9}$ pb in a short term. This will require to obtain an exposure of 3000 kg.d.

In order to reduce the beta and gamma backgrounds, we developed an improved detector design, named ”Full InterDigit” (FID). These 800 g crystals are equipped with two NTD heat sensors, and are covered by interleaved electrodes on all their surface. There is therefore no ”guard” region anymore inside the crystal volume. Both the increase of crystal mass and the removal of guard regions increase the fiducial mass for each individual detector by a factor ∼4.

First calibrations of these detectors have also demonstrated an improvement of the gamma-ray rejection over the original ID detectors, as presented in Fig. 7. We plan to install 40 FID800 detectors, corresponding to ∼24 kg fiducial volume in 2012.

Infrastructure upgrades (cabling, cold electronics, cryogenics and acquisition) are necessary to host these new detectors, and will also reduce the neutron budget within the cryostat. In
Figure 7. Ionization yield distribution as a function of recoil energy for the fiducial events recorded in two FID800 detectors during gamma-ray calibrations. Although the fiducial statistics is larger than what was collected on ID detectors, no anomalous event leaks in the NR region contrarily to what is observed on Fig. 3.

addition, an inner polyethylene shield will be installed to reduce the flux of fast neutrons coming from outside the cryostat.

Finally, let us mention that various efforts are also ongoing in order to improve the sensitivity of EDELWEISS detectors to low-mass WIMPs, of typical mass $\sim 10$ GeV.

References
[1] http://edelweiss.in2p3.fr/
[2] Armengaud E et al. 2011 Phys. Lett. B 702 329
[3] Ahmed Z et al. 2011 Phys. Rev. D 84 011102
[4] Broniatowski A et al. 2009 Phys. Lett. B 681 305
[5] Loaiza P, these proceedings
[6] Eitel K, these proceedings
[7] Yellin S 2002 Phys. Rev. D 66 032005
[8] Ahmed Z et al. 2010 Science 327 1619