Status of the EDELWEISS-III Dark Matter search

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Abstract. EDELWEISS is a direct dark matter search program looking for Weakly Interacting Massive Particles (WIMPs) in the GeV-TeV mass range using an array of cryogenic Ge mono-crystals. These high-performance detectors are read out simultaneously by NTD thermal sensors and by surface electrodes. They are installed in the deepest European underground laboratory in Modane. The third phase of the experiment is currently ongoing with a major upgrade of the setup. New FID800 Ge bolometers have been developed and the shielding has been improved to lower the background. In addition, the cryogenic and acquisition systems have been upgraded to improve energy resolutions and thresholds.

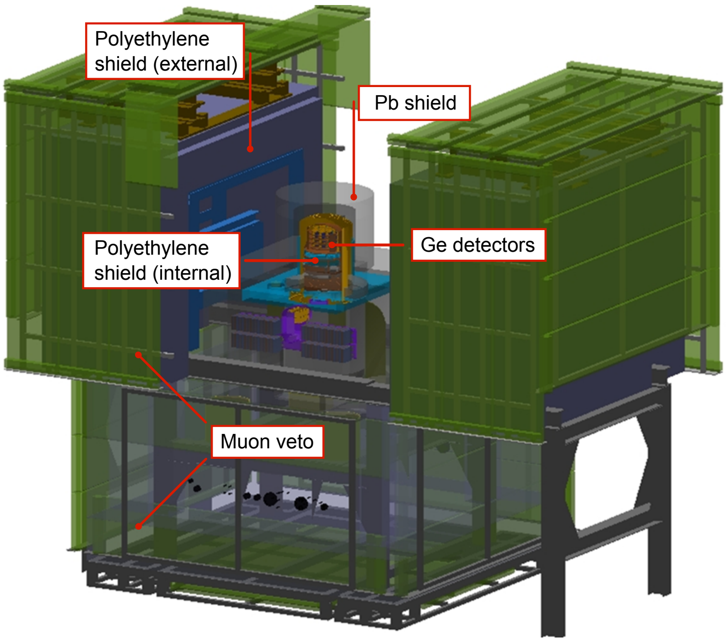
1. The EDELWEISS experiment

1.1. Experimental setup

The EDELWEISS experiment is operated in the deepest underground laboratory in Europe, the *Laboratoire Souterrain de Modane* (LSM). The 4800 m.w.e mountain rock thickness above the experiment allows to reduce the cosmic muon flux by a factor 10^6, down to 5 muons/m^2/day [1]. Remaining muons going through the experiment are tagged using an active muon veto system surrounding the setup (Fig. 1 left). Due to the 46 modules of plastic scintillator covering a surface of 100 m^2, a geometric coverage of 98% for through-going muons is achieved. In addition, a 50 cm layer of polyethylene (PE) shield is used to moderate radiogenic neutrons. A 20 cm lead shield is used to stop external γ and β, which are further reduced in the copper of the cryostat where the Ge detectors are cooled down to 18 mK. Inside the cryostat, additional pieces of lead and PE are used to shield the bolometers from the cold electronics (Fig. 1 right). Thanks to the external shields, the background in the detectors is mainly coming from inside the cryostat.

1.2. Germanium bolometers

The EDELWEISS detectors are high-purity Ge mono-crystal bolometers equipped with Neutron Transmutation Doped Ge sensors used as thermistors and covered by concentric aluminum ring electrodes. Due to the simultaneous measurement of heat and ionization, it is possible to distinguish on an event-by-event basis electronic recoils (ER) induced by γ or β from nuclear recoils (NR) induced by WIMPs or neutrons. Indeed, the ratio of ionization over recoil energy, the so-called ionization yield Q, is equal to 1 for ER by normalization to ^{133}Ba calibration and $\simeq 0.3$ for NR as described by the Lindhard formula [2]. This powerful discrimination is



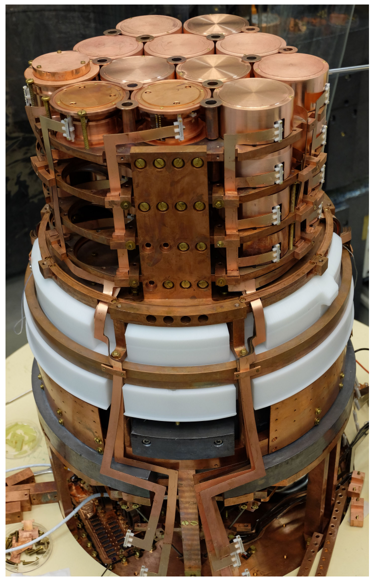


Figure 1. Left: schematic of the EDELWEISS-III setup showing in the center the cryostat hosting the bolometers, surrounded by passive lead and polyethylene (PE) shields and an active muon veto in order to protect the detectors from various backgrounds. Right: view of the opened cryostat equipped with 36 FID germanium bolometers in their copper housing, which are shielded from the cold electronics below using internal lead and PE shields.

reinforced by the rejection of surface events which are most likely α and β particles. These surface events are particularly dangerous as they may suffer from bad charge collection and are thus susceptible to leak into the NR band where WIMP signals are expected. The discrimination of such events is possible thanks to the electrode design: electrodes are alternatively biased ($O(1\,\mathrm{V})$) and bounded, defining a fiducial volume for which the charge collection is complete and a surface volume for which it may not. One set of electrodes, the collecting electrodes, has a higher bias and collects charges from the bulk whereas events with a signal on the other set (veto electrodes) are efficiently rejected. Indeed, as can be seen Fig. 2, the electric field lines in the fiducial volume are perpendicular to the detector surface and charges are drifted to the collecting electrodes at the top and the bottom of the detector. At the surface, the field lines are parallel to the detector surface and charges are drifted to the veto and collecting electrodes on one side. Thus, by rejecting events with veto signal, surface events can be discriminated.

2. Results from the second phase of the experiment EDELWEISS-II

Before detailing the numerous improvements which were carried out for EDELWEISS-III, here is a review of EDELWEISS-II results and what we learned from it. EDELWEISS-II was originally designed to detect WIMPs in the mass range [10,100 GeV]. For this purpose, 10 so-called *Inter-Digitized* (ID) detectors of 400 g each were run for a continuous data taking period of 13 months from April 2009 to May 2010.

2.1. Standard WIMP analysis

The standard WIMP analysis [4] is based on a total effective exposure of 384 kg·days after all cuts. 5 events were observed in the 90% C.L. NR band in the region of interest with recoil

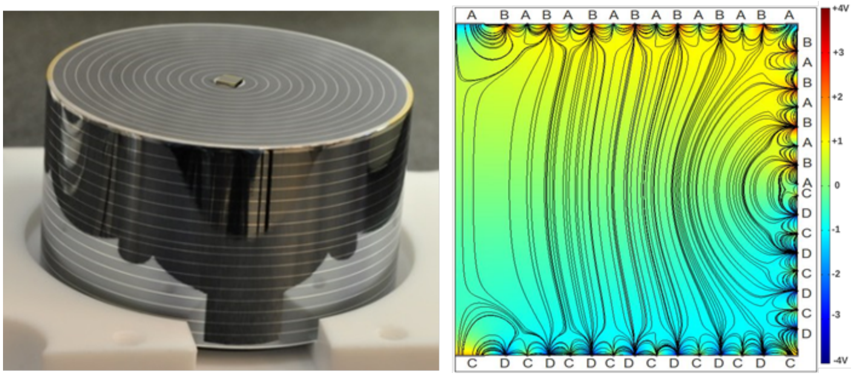


Figure 2. Photo and sketch of the electric field lines for a cross section of a FID800 detector. The color code indicates the electric potential, the electric field lines being drawn in black. Charges induced by fiducial events are collected by the B and D electrodes only whereas charges induced by surface events are partly collected by at least one of the veto electrodes A and C.

energy [20, 200 keV] whereas 3.0 events were expected from background (1.4 neutrons from ambient radioactivity, 0.9 γ-ray leaking, 0.4 muon-induced neutrons and 0.3 unrejected surface events). These 5 events were interpreted as an upper fluctuation of the background and limits on the spin-independent (SI) WIMP-nucleon cross section were derived, leading to an exclusion limit of $\sigma_{SI} < 4.4 \times 10^{-8}$ pb at 90% C.L. for a WIMP mass of 85 GeV (Fig. 3 left). Limits on spin-dependent interaction cross-section were also derived [4]. As both CDMS and EDELWEISS experiments use the same target, their results were combined [5] leading to an exclusion limit of $\sigma_{SI} < 3.3 \times 10^{-8}$ pb (90% C.L.) for a WIMP mass of 90 GeV, based on a combined exposure of 614 kg·days.

2.2. Low mass WIMP analysis
In order to investigate the various signal claims at low mass WIMPs, a restricted data set from EDELWEISS-II was used by selecting detectors with low background and good performance at low energies down to 5 keV. By choosing an upper threshold of 20 keV, this analysis is completely independent from the standard WIMP analysis and covers a WIMP mass range of [7, 30 GeV]. Four out of the 10 ID detectors were used and stronger quality cuts were applied, leading to an exposure of 113 kg·days. Up to 3 events (depending on the WIMP mass) were observed in the WIMP search region, compatible with the expected background of 2.9 events ($<$ 1.7 ambient neutrons and $<$ 1.2 misidentified γ's). From this measurement, an exclusion limit of $\sigma_{SI} < 1.0 \times 10^{-5}$ pb at 90% C.L. was derived (Fig. 3 left), which was excluding DAMA/LIBRA [7] and CRESST [8] claims and significantly constraining the CoGeNT [9] signal.

2.3. Axion search
Axions are hypothetical dark matter particles which could induce an electronic recoil in the bolometers after production of γ's via the Primakoff effect or electrons via the axio-electric effect. The EDELWEISS-II sensitivity to electronic recoils down to 2.5 keV makes the experiment sensitive to axions. Due to the low-radioactivity setup and the fiducial volume selection, a background level down to 0.3 events/kg/day/keV could be achieved. The full EDELWEISS-II data set with relaxed cuts was used, with an exposure of 484 kg·days. Axion production in the Sun and axions as dark matter particles were studied considering different scenarios on the axion couplings with photons and electrons, and the effective axion-nucleon coupling for ^{57}Fe [10]. Combining all obtained results, one can exclude the mass range 0.91 eV $<$ mA $<$ 80 keV

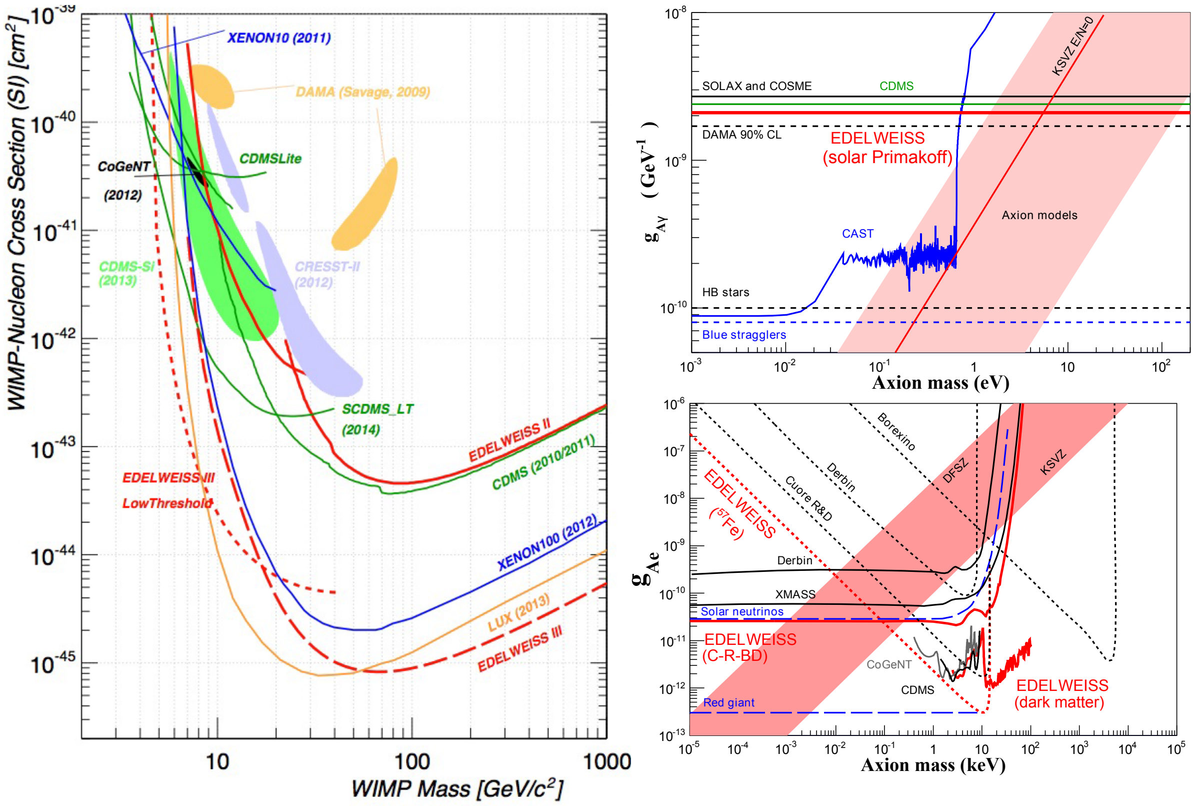


Figure 3. Left: Upper limits on the spin-independent WIMP-nucleon interaction cross section versus the WIMP mass. EDELWEISS-II results corresponding to [4] and [6] are drawn with solid red lines. EDELWEISS-III projection for standard and low mass WIMPs are marked using red dotted lines. Right: EDELWEISS-II limits on $g_{A\gamma}$ coupling from the solar Primakoff flux and on g_{Ae} coupling versus the axion mass (red lines) [10].

for Dine-Fischler-Srednicki-Zhitnitskii (DFSZ) axions and 5.73 eV < mA < 40 keV for Kim-Shifman-Vainstein-Zakharov (KSVZ) axions (Fig. 3 right).

3. Improvements for EDELWEISS-III

The EDELWEISS-II sensitivity reached in 2010 was mainly limited by misidentified γ's and radiogenic neutrons produced by (α,n) reactions in the cabling inside the cryostat. In addition, the low mass WIMP analysis showed the necessity to improve energy resolutions and lower the thresholds. In order to achieve the EDELWEISS-III goal to probe WIMP-nucleon cross sections down to 10^{-9} pb, many upgrades were made to reduce the backgrounds and improve performance at low energies. 36 so-called *Fully Inter-Digitized* (FID) detectors of a mass of 800 g each with improved background rejection capabilities were installed in the cryostat. These new detectors are twice more massive than the previous generation and benefit from a fiducial volume increase from 40% to 75% of the detector volume. This was achieved thanks to the new electrode design which replaced the planar electrodes on the lateral surface with ring electrodes. Thus the detection mass was increased from 1.6 kg in EDELWEISS-II to more than 20 kg in EDELWEISS-III.

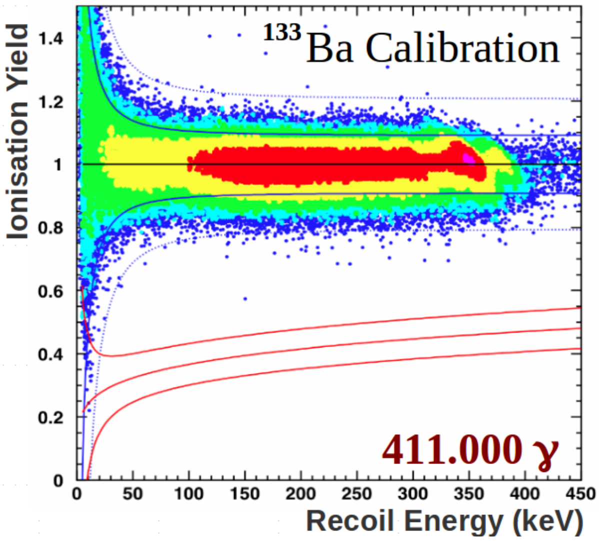


Figure 4. Ionization yield as a function of the recoil energy in keV for events from γ-calibration using a ^{133}Ba source. The dashed and continuous blue lines are respectively the 90% C.L. and the 99.98% C.L. electronic recoil bands whereas the continuous red lines corresponds to the 90% C.L. nuclear recoil band. There is no single γ event leaking in the nuclear recoil band over the 411 000 measured γ.

3.1. Passive background rejection

In order to reduce the neutron background by a factor 100 down to $(0.8 - 1.9) \times 10^{-4}$ events/kg·day,cables inside the cryostat were replaced by designed in-house radiopure Cu Kapton cabling. Additional internal and external PE shields were installed, notably between the internal roman lead shield and the bolometers to protect against neutrons from the cold electronics mainly arising from (α,n) reactions (Fig.1 right). One also expects a decrease of the internal γ-background by a factor between 2 and 6 down to 14-44 events/kg·day thanks to the new low activity (NOSV) copper screens of the cryostat. It should be noted that the radon level near the bolometers is controlled and reduced down to a few tens of mBq/m^3. Efforts are also ongoing to reduce the muon-induced neutron background by at least a factor 10. For this purpose, 4 additional scintillator panels were installed to cover the detection gap located above the cryostat. A calibration campaign is currently ongoing to determine the position-dependent module response which will, together with a detailed MC simulation of the muon propagation, enable a more precise determination of the muon-induced neutron background for the modified EDELWEISS-III setup.

3.2. Active background rejection

The active rejection of misidentified γ's which were limiting the sensitivity in the previous phase was shown to be considerably improved in EDELWEISS-III. This background was arising from multiple γ-scattering which deposit energy in the bulk and near the detector surface but with a veto signal below threshold. These events can now be rejected more efficiently due to the new electrode design. The rejection power of γ's was measured using a ^{133}Ba source and determined to be more than 5 times better than in EDELWEISS-II: out of the $> 4 \times 10^5$ measured γ's, none leaked into the NR band above 20 keV, leading to a rejection factor $< 6 \times 10^{-6}$ NRs/γ (Fig.4). The new electrode configuration also induces a better discrimination power of surface events which was measured using a ^{210}Pb source to be >1.5 times better than in EDELWEISS-II with $< 4 \times 10^{-5}$ misidentified β's per evt/kg·day in EDELWEISS-III [11].

3.3. Energy resolutions and threshold

New cryogenic and electronic systems were installed to improve the performance at low energies. In order to reduce the microphonic noise that decreases the heat resolution, the pulse tubes near the cryostat were replaced by Gifford-McMahon thermal machines outside of the shields, connected to the cryostat using a cryoline. Concerning the electronic system, the active feedback system necessary to reset the bolometers' ADC was replaced by a relay system. No more needed resistors were removed to avoid Johnson noise and thus improve the noise level at low energies. These upgrades lead to the lowering of the average FWHM of the heat baselines from 1.2 keV to 1.0 keV and of the ionization baselines from 900 eV to 600 eV. Thanks to these improvements, a lower analysis threshold can be achieved as well as a sensitivity down to 5 keV necessary for the detection of low mass WIMPs. In addition, the installation of an integrated DAQ system improves the reliability of the data taking and the event building: all the individual bolometer data are processed through a single crate which provides a common clock for the bolometer data acquisition as well as for the muon veto system. In addition, the DAQ system is able to do a real time processing of the data stream (e.g. take a trigger decision) in parallel for all channels. Based on this fast trigger decision, it also allows to read out fast sampled (40MS/s) traces of ionization channels which provide time-resolved ionization signals. This additional information can be used to localize the event vertex along the z-axis or identify multiple scattering events within the detector. We are currently studying the potential of this new data to reject multiple scattering events as well as to have complementary tool for surface event rejection.

4. Conclusion

EDELWEISS-III is currently taking data since August 2014, aiming at first to obtain a background-free exposure of 3000 kg·days at the end of 2015. The final goal is to measure 12000 kg·days exposure for which background should start to appear, leading to a sensitivity to a spin-independent WIMP-nucleon cross section of 10^{-9} pb.

Acknowledgments

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