The EDELWEISS dark matter search: status and perspectives

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Abstract
EDELWEISS is a phased direct dark matter search programme whose primary goal is to search for WIMPs in the GeV-TeV mass range. For that purpose, a set of cryogenic Ge mono-crystals read out simultaneously by NTD thermal sensors and by surface electrodes is installed in the Modane underground laboratory (LSM, France). The second phase of the experiment was recently completed, setting new limits on the spin-independent WIMP-nucleon scattering cross section for WIMP masses above 7 GeV. In addition, competitive limits on axion couplings have been deduced. In 2012 and 2013, a substantial upgrade of the setup was undertaken to significantly improve the sensitivity. This upgrade includes new 800-g Ge bolometers, reduced background through improved shielding as well as better energy resolution and a highly integrated electronic readout. The scientific results of EDELWEISS-II are reviewed. We describe the EDELWEISS-III setup, its physics prospects and first data recorded in commissioning runs.

Keywords: Dark Matter, WIMP search, cryogenic Ge detectors

1. The EDELWEISS experiment
The EDELWEISS experiment searches for dark matter with the use of germanium bolometers, with an improved background rejection based on an interdigitized electrode design (ID) [1]. With an operating temperature of the detectors of 18 mK, one can simultaneously measure phonon and ionization signals after an energy deposit in the germanium crystal. The ratio of the two signals, the so-called Q-value or ionization yield, is different for nuclear and electron recoils, with nuclear recoils having \( Q \sim 0.3 \) when normalized to \( Q = 1 \) for electron recoils. This separation in the ionization yield is well understood and quantitatively described [2] and leads to a powerful rejection of \( \beta \)- and \( \gamma \)-backgrounds. Additional rejection power arises from the special electrode arrangement of interdigitized electrodes (Fig. 4) providing rejection of surface events [1]. The annular aluminum electrodes are evaporated onto the Ge mono-crystal and collect electrons and holes depending on their polarisation, resulting in low electric field values of typically 2 V/cm. The temperature increase is measured using neutron-transmutation-doped germanium (NTD) as a temperature sensor. The ID detectors used in the second phase of the experiment, EDELWEISS-II, had a mass of 400 g each with interleaved electrodes on the top and bottom surfaces, resulting in a fiducial volume of about 40%, or 160 g per detector [3]. For the EDELWEISS-III phase, larger detectors of 800-g mass with interleaved electrodes also on the lateral surface (Fig. 4) were developed, so-called fully interdigitized (FID) bolometers. This increased the fiducial mass to about 75% or 600 g per detector.
Fig. 1. Left: Schematic view of the EDELWEISS experimental setup, from outside to inside: muon veto panels (green), PE shielding (light grey), Pb shield (dark grey), cryostat (dark yellow). Right: View into the open cryostat with mounted Ge detectors in their Cu holders above an internal PE shield (status as of March 2014 with 36 FID800 detectors of EDELWEISS-III mounted).

The experimental setup is located in the Laboratoire Souterrain de Modane (LSM), an underground lab in the Fréjus road tunnel in the French-Italian Alps. The laboratory profits from a shielding of 4850 m.w.e., which reduces the muon flux down to about $5 \mu/m^2/day \ [4]$. A general overview of the setup is shown in Fig. 1: The central part of the experiment is a dilution cryostat which can host up to 40 kg of detectors. A Pb layer of 20 cm thickness shields the bolometers against an external $\beta$- and $\gamma$-background while 50 cm of polyethylene is used to moderate neutrons. An additional layer of polyethylene is installed between the bolometers and the lead layer in the EDELWEISS-III setup to further reduce the neutron background. A muon veto system (>98% coverage) consisting of 100 m$^2$ of plastic scintillator to tag remaining cosmic muons completes the installation. In addition, a continuous control of the Rn level (typically a few mBq/m$^3$ is performed near the cryostat), and a $^3$He-gas detector is installed inside the shields to monitor the thermal neutron flux. A neutron counter system based on 1 m$^3$ of Gd-loaded liquid scintillator [5] was used in 2009-2012 to study muon-induced neutron background. The EDELWEISS-II phase has been completed, and the upgrade to EDELWEISS-III has been finished and is described in Sec. 3. The scientific goal of EDELWEISS-III is to reach a sensitivity of $\sigma_{SI} \sim 10^{-9} \, \text{pb}$ for the WIMP-nucleon spin-independent (SI) cross section by 2015/2016.

2. EDELWEISS-II results

In the second phase of the experiment the EDELWEISS collaboration successfully operated ten 400-g ID detectors over a period of 14 months from April 2009 to May 2010. The data set includes data from two detectors during an initial run between July and November 2008. Here, we shortly summarize the main results of this measurement period.

For WIMP masses of $m_\chi \gtrsim 50 \, \text{GeV}$, the analysis was optimized to get a maximum exposure in a recoil energy range where the behavior of all of the ten detectors was homogeneous and well understood. It resulted in 384 kg·d of total effective exposure, accounting for fiducial cuts and a 90% effective region of interest. Five nuclear recoil candidates were observed above an a priori set threshold of 20 keV. In the background conditions of EDELWEISS-II (see below), the result was interpreted in terms of limits on the cross section of spin-independent interactions of WIMPs and nucleons: $\sigma_{SI} < 4.4 \cdot 10^{-8} \, \text{pb} \ (90\% \ C.L.)$ for a WIMP mass of 85 GeV (Fig. 6)[3]. New constraints were also set on models where the WIMP-nucleon scattering is inelastic [3]. As both EDELWEISS-II and CDMS experiments use the same target material of germanium and both experiments had null results, the two collaborations decided to perform a combined analysis. This allowed an increase in the total data set to about 614 kg·d equivalent exposure and an improvement in the
sensitivity to $\sigma_{SI} < 3.3 \cdot 10^{-8}$ pb (90% C.L.) for a WIMP mass of 90 GeV, where the combined analysis is most sensitive [6].

To investigate a potential signal from low mass WIMPs ($m_\chi \lesssim 10$ GeV) where for e.g. $m_\chi = 10$ GeV the maximal expected recoil energy is of the order of 10 keV, a restricted data set was used, selected on the basis of detector thresholds and backgrounds, for which a low-background sensitivity to nuclear recoils down to 5 keV could be achieved. The data quality cuts resulted in only four out of the ten detectors being used, with a total exposure reduced to 113 kg $\cdot$ d [7]. For WIMPs of 10 GeV mass, one event was observed in the WIMP search region with an expected background of 2.9 events, which leads to $\sigma_{SI} < 1.0 \cdot 10^{-5}$ pb (90% C.L.) [7] (Fig. 6). This special analysis extended the sensitivity of EDELWEISS-II down to WIMP masses below 20 GeV and considerably constrained the parameter space associated with the claim of signals reported by the CoGeNT, DAMA and CRESST experiments.

EDELWEISS is primarily designed for the direct WIMP search via nuclear recoils However, the fact that germanium bolometers are also sensitive to low-energy electron recoils allows a search for such recoils potentially induced by solar or dark matter axions. The same data set was thus analyzed to probe scenarios involving different hypotheses on the origin and couplings of axions. The extensive study is described in [8], and here we summarize that; combining all obtained results we exclude a mass range $0.91 \text{ eV} < m_\Lambda < 80 \text{ keV}$ for DFSZ axions and $5.73 \text{ eV} < m_\Lambda < 40 \text{ keV}$ for KSVZ axions, setting, for some axion masses, the most stringent limits so far.

The goal of EDELWEISS-III is an improvement in sensitivity by a factor of 20 to 40. To achieve this, detailed knowledge of the background in EDELWEISS-II is required as a prerequisite to further suppress dominant background sources. We carried out Monte-Carlo simulations based on Geant4 for the complete EDELWEISS-II setup to study gamma and neutron backgrounds coming from radioactive decays in the setup and shielding, and normalized the expected background rates to the measured material radiopurity (or upper limits) of all components [9]. Figure 2 demonstrates the excellent agreement of MC model and measured gamma background over the entire energy range as well as in the relevant low energy window (right plot). The expected gamma ray event rate in EDELWEISS-II at 20-200 keV agrees with the observed rate of 82 events/kg/day within the uncertainties in the measured concentrations. The most prominent gamma source could be identified to be the internal Cu plates and the Cu screens of the cryostat [9] which have been consequently replaced by NOSV copper for EDELWEISS-III. The neutron rate from radioactivity was estimated to be less than 3.1 events at 90% C.L. at 20-200 keV and for an effective exposure of 384 kg $\cdot$ d, or $< 8.1 \cdot 10^{-3}$ events/kg/d. The rate of muon-induced neutrons was deduced in a dedicated study making use of the modular muon veto system and the spatial reconstruction of muon tracks (Fig. 3) and resulted in $2 \cdot 10^{-3}$ events/kg/d (90% C.L.) for EDELWEISS-II [4]. Note that the main contribution is due to a short period of malfunctioning of the veto system. Consequently, the expected muon-induced background for EDELWEISS-III is considerably lower.
3. The EDELWEISS-III upgrade

With the results achieved with EDELWEISS-II and the thorough investigation of the background components, an upgrade of the experiment was started with an envisaged sensitivity improvement of up to a factor 40, surpassing in part the world-best sensitivity reached at the end of 2013 by the LUX experiment [10].

3.1. Hardware changes and improvements

The actual EDELWEISS-III upgrade concerns all aspects of the experiment: New copper thermal screens were produced out of more radiopure (NOSV) copper, which reduces the intrinsic gamma background. New polyethylene shields are installed inside the cryostat between the detectors and the lead castle (Fig. 1) to protect against neutrons arising mainly from (α,n) reactions in the cold electronics. The detector-near cabling was replaced by radiopure Cu Kapton cables. Additional modules of the muon veto system were installed, and further optimization of its operation is ongoing in order to improve its efficiency. The analog front-end electronics has been upgraded such that DAC-controlled mechanical relays are used instead of feedback resistors of charge sensitive preamplifiers [11]. The use of relays is expected to avoid Johnson noise contributions from resistances and thus to improve the low frequency noise level. It also allows to move electronics farther away, and thus reduces its radioactive influence on the detectors. A new electronic DAQ system has been developed and implemented reading up to 60 bolometers including the readout of the muon veto system and synchronisation of all detectors. The new design also integrates the readout of time-resolved ionisation channels with a sampling rate of 40 MSPS (compared to 100 kSPS) to further improve the discrimination power between fiducial and surface events [1]. R&D on a HEMT-based front-end readout is ongoing to lower the energy threshold and thus improve the low-mass WIMP search. Finally, in order to handle a significantly increased data flow, a multi-tiered data structure, analysis toolkit and data processing management system [12] has been developed for EDELWEISS-III.

3.2. Performances

The centerpiece of the EDELWEISS-III upgrade are new FID detectors with twice the mass (800 g) and increased fiducial volume (∼600 g) have been developed (Fig. 4). In dedicated calibration runs performed in 2013, these detectors were confirmed to have better rejection of γ-events compared to the previous ID400 detectors, e.g. out of > 4 · 10⁵ γ-events recorded in a ¹³⁵Ba calibration, none leaked into the region of interest, i.e. into the nuclear recoil band between 20 and 200 keV. Recently, two of these detectors were also tested for rejection of surface events (Fig. 5) and showed also a better rejection power of 4 · 10⁻⁵ above 15 keV recoil energy (90% C.L.) compared to a previously measured value of 6 · 10⁻⁵ for ID bolometers above 20 keV.

In March 2014, 36 FID800 detectors were mounted into the cryostat (Fig. 1 right) and commissioning runs with the almost complete detector set have started. The plan of EDELWEISS-III is to acquire a
background-free exposure of 3000 kg · d within half a year of operation and to reach a WIMP-nucleon scattering cross section sensitivity of $5 \cdot 10^{-9}$ pb by the end of 2014. After this first milestone, continued data taking is planned to run up to an exposure equivalent to 12000 kg · d reaching eventually $1 \cdot 10^{-9}$ pb (Fig. 6). The ongoing research builds a good ground for the EURECA project [13, 14], a next generation dark matter experiment with a multinuclei target of up to 1000-kg mass. EURECA is supported by different European dark matter groups and a closer collaboration with SuperCDMS experiment is foreseen. EURECA will probe in its 1-tonne phase a WIMP-nucleon SI interaction down to $10^{-11}$ pb covering a major part of the parameter region favored by post-LHC1 CMSSM [15].

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Fig. 5. Suppression of surface events in an FID800 detector induced by an irradiation with a $^{210}$Pb source with $\beta$ decays of $^{210}$Pb and $^{210}$Bi, and subsequent $\alpha$ decays of $^{210}$Po with their respective recoiling $^{206}$Pb nuclei with recoil energies up to 100 keV and very low $Q$-value.

Fig. 6. Results with experimental evidences (filled regions) and exclusion curves (solid lines) of existing experiments and projected sensitivities (dotted lines). Also shown are favored parameter regions in CMSSM models.