33RD INTERNATIONAL COSMIC RAY CONFERENCE, RIO DE JANEIRO 2013
THE ASTROPARTICLE PHYSICS CONFERENCE

The EDELWEISS dark matter search: Recent results and outlook for EDW-3

M. KLEIFGES[1] FOR THE EDELWEISS COLLABORATION.

[1] *Institut für Prozessdatenverarbeitung und Elektronik, KIT - Karlsruher Institut für Technologie, Germany*

Matthias.Kleifges@KIT.edu

Abstract: The EDELWEISS experiment uses an array of cryogenic Ge bolometers to detect signals from scattering of Weakly Interacting Massive Particles (WIMPs) off Ge nuclei. Heat and ionization signals for each individual event are read out via NTD-thermistors and interleaved Al-ring electrodes, respectively. With this technique, an excellent active suppression of radiogenic background is achieved. In addition to a standard WIMP search, recent results of a search for low mass WIMPs in the region between 5 GeV and 30 GeV, exclude the DAMA and CRESST signal regions at 90% C.L., as well as parts of the CoGeNT allowed region. In 2013, the 3rd phase of the experiment has started with upgraded cryogenic infrastructure, additional internal shielding and an enlarged detector array of 800-g bolometers. A sensitivity improvement beyond the actual best upper limits is anticipated after a six-month cryogenic run. The paper reviews the current EDELWEISS results and gives an outlook on the expected sensitivity of EDELWEISS-III.

Keywords: Dark Matter, Cryogenic Ge detectors, bolometer, direct search for WIMP, EDELWEISS experiment.

1 Dark matter search with EDELWEISS

Supersymmetric (SUSY) theories, and other extensions of the standard model of particle physics, predict plausible candidates for Weakly Interacting Massive Particles (WIMPs), which could explain the evidence of dark matter. The EDELWEISS experiment uses Ge bolometers for a direct search of dark matter WIMPs, i.e. for the detection of an elastic scattering process between a dark matter particle and a Ge crystal.

EDELWEISS is located in the underground laboratory Laboratoire Souterrain de Modane (LSM) which provides by the rock of the Alps above an average overburden of 4800 m.w.e. This massive shielding reduces the flux of cosmic muons to about 5.4 $m^{-2}day^{-1}$ [1] and the flux of thermal neutron to about 0.3 $cm^{-2}day^{-1}$. Since neutrons are a prominent background source, their rate is constantly monitored by a Rn monitor, by ^{3}He proportional counters [2], and by a 1 m^3 Gd-loaded liquid scintillator[1] for the muon-induced neutron fraction [3].

The central part of the EDELWEISS experiment is the cryostat, which can contain up to 40 kg of Ge detectors (see figure1). It is cooled by a dilution refrigerator to keep the temperature of the bolometers constant at 18 mK. A 20 cm lead shield surrounding the cryostat reduces the external γ-ray background effectively. Further shielding against neutrons is realized by a layer of 50 cm of polyethylene and the whole setup is surrounded by an active muon veto system composed of 100 m^2 of plastic scintillators bars for muon tagging.

Particle interactions are detected in EDELWEISS by measuring the bolometric energy in neutron transmutation doped (NTD) Ge heat sensors and - in addition and complementary - by measuring the ionization signal in electrodes under the presence of an electric field. This technique allows distinguishing nuclear recoil and electron recoil interactions due to the different ionization yield of the process which is a key advantage for background suppression. For best measurement of the ionization signal, Al rings are vapor-deposited as concentric electrodes on the top and bottom sides of the cylindrical Ge crystals. This *interleaved electrodes design* (ID) of EDELWEISS-II bolometers is shown in figure 2 (left). The signals from veto and fiducial electrodes allow discriminating bulk events in the fiducial volume (green region) from surface events (red and blue regions) efficiently [4].

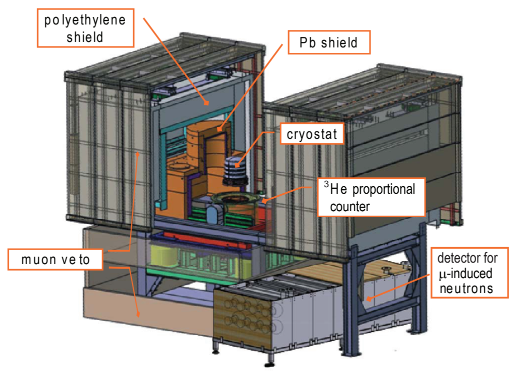

Figure 1: Layout of the EDELWEISS setup: The cryostat housing the Ge bolometers is surrounded by several layers of shielding materials (20 cm lead, 50 cm polyethylene) and an active muon veto system. Background neutrons are monitored using different type of neutron counters.

The ID technique was further developed for the setup of EDELWEISS-III: in the new design the guard electrodes (blue) are omitted and the alternating pattern of veto and fiducial electrodes is continued to the cylindrical surface (figure 2 (right)). These *fully interleaved detectors* (FID) are more difficult to produce, but they provide a considerably enhanced fiducial volume.

1. This detector was dismantled in October 2012.

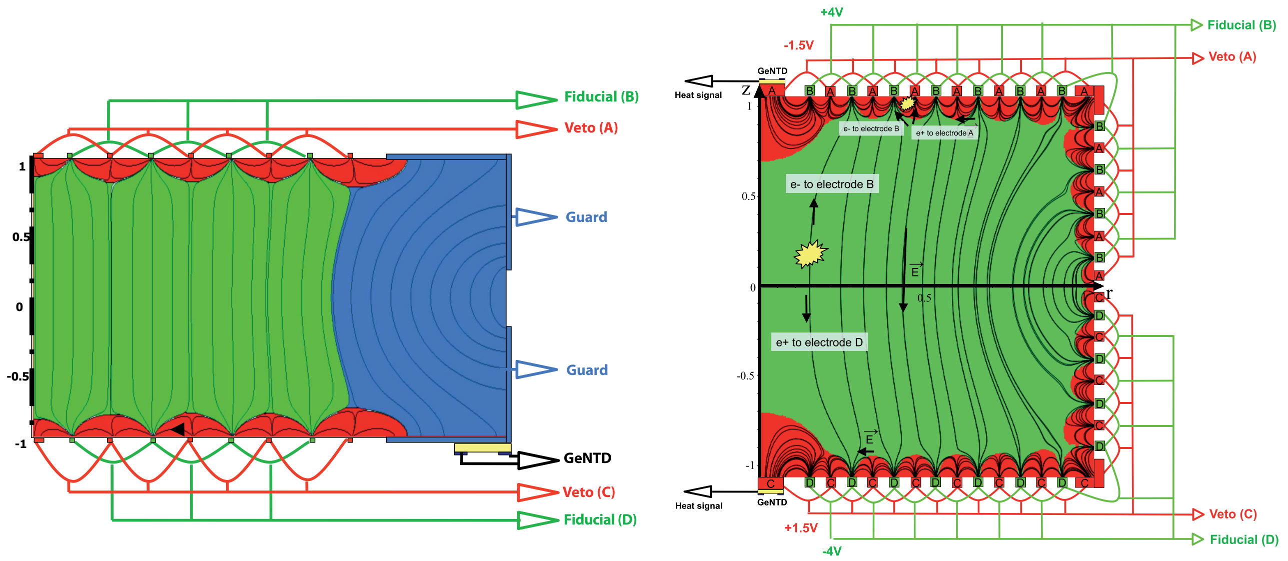

Figure 2: Cross section through a Ge detector showing the scheme of interleaved ring electrodes. The inner (green) volume ensures best charge collection and is used for the WIMP search. In EDELWEISS-II, electrodes are deposited on the top and bottom only (left). A large fraction of volume (blue) is lost close to the guard ring on the cylindrical side. This is not the case for EDELWEISS-III FID detectors (right) where the scheme of interleaved electrodes is continued on the side surface.

2 Results from EDELWEISS-II

The EDELWEISS collaboration operated ten ID detectors of 400 g each under stable conditions for 14 months from April 2009 to May 2010 and in addition two detectors during an initial run from July to November 2008. This data set was analyzed with a cut on the recoil energy $E_r > 20$ keV. The energy threshold was defined a priori to search for classical supersymetric WIMPs with masses $M_\chi > 50$ GeV in an energy range where the detection efficiency is energy independent. We sum up here the main results of the analysis which is described in detail in [5].

The energy resolution (averaged over the contributing detectors) for the heat channel and ionization channel was about 1.2 keV (FWHM) and 0.9 keV (FWHM), respectively. The data set with a total effective exposure of 384 kg·day contained five events in the nuclear recoil band, while the estimated background was three events. This result was interpreted in terms of limits on the cross section of spin-independent interactions of WIMPs and nucleons. For a WIMP mass of 85 GeV a cross section of 4.4×10^{-8} pb was excluded at 90% C.L.(bold red line in figure 3).

The CDMS and EDELWEISS collaborations have also published a combined result of their efforts in searches for dark matter with Ge detectors [6]. With the consolidated data set of 614 kg·day equivalent exposure the upper limit of the spin-independent cross section was improved by a factor of about 1.6. The analysis is most sensitive to WIMPs around 90 GeV, and a spin-independent cross section above 3.3×10^{-8} pb is excluded at 90% C.L.

Other experiments [7, 8, 9] using different detector types have found hints for WIMPs with masses of 10 GeV or below and with cross sections for spin-independent scattering on a nucleon of about 10^{-4} to 10^{-5} pb (see contour lines in figure 3). The maximum expected recoil energy for scattering of these low mass WIMPs on nuclei is at most 10 keV. Hence, a complementary and independent analysis method to exploit the low-energy range below the 20 keV threshold is required.

The choosen method [10] uses an exposure of 113 kg·day extracted from the 2009-2010 data set using a more stringent selection based on detector performance required by the lower analysis threshold. In particular, only four out of ten detectors in operation passed the quality cuts. Detectors with malfunctioned electrodes and/or poor energy resolution in any electronic channel were rejected. One detector was excluded from the data set due to its vicinity to a relatively intense calibration source of ^{210}Pb, another one because of its four times higher γ-ray background level. Individual events were rejected when they occurred in coincidence with activity in any other operating bolometer or in coincidence with the muon veto system. Other event

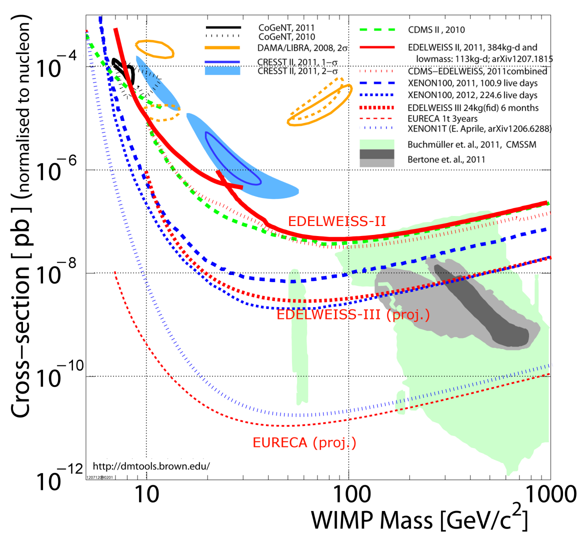

Figure 3: Upper limits (90% C.L.) on WIMP-nucleon spin-independent cross sections as a function of WIMP mass for various experiments (colored lines). The green and grey shaded areas correspond to theoretical SUSY predictions.

selection cuts (e.g. for the fiducial volume) were identical to those of the high mass WIMP analysis in [5].

The estimate of the nuclear recoil energy $E_r^{(h)}$ is derived solely from the heat signal and a correction for the Neganov-Luke effect is applied. The varying efficiency and noise conditions over time play an important role for results close to the trigger threshold. To take this into account, the efficiency as a function of $E_r^{(h)}$ was derived from the resolution of the heat channel and the adaptive trigger threshold. The analysis was verified with the constant flat Compton plateau in γ-ray calibration data.

Then, for a given WIMP mass and for every contributing detector, the expected signal density map in the $(E_r^{(h)}, E_i)$ plane was calculated from the efficiency and energy resolution function, with E_i being the ionization energy. An example for a hypothetical 10-GeV WIMP is shown in figure 4. The red contour line surrounds the region with integral 90% WIMP signal strength below the 95% γ-ray rejection cut (blue dashed line). The figure also shows events from neutron calibration (grey dots) which spill over into the search contour and hence confirm the detector sensitivity to WIMP search. Assuming Poisson statistics, the 90% C.L. upper-limit cross section can be derived from the observed number of events between 1 and 3, the background expectation of about 2 events, and the integrated signal strength. The obtained limits confirm the good sensitivity of EDELWEISS-II for masses $M_\chi \leq 20$ GeV. The regions favored by DAMA/LIBRA and CRESST are completely excluded and the region of CoGeNT is partly excluded (see figure 3).

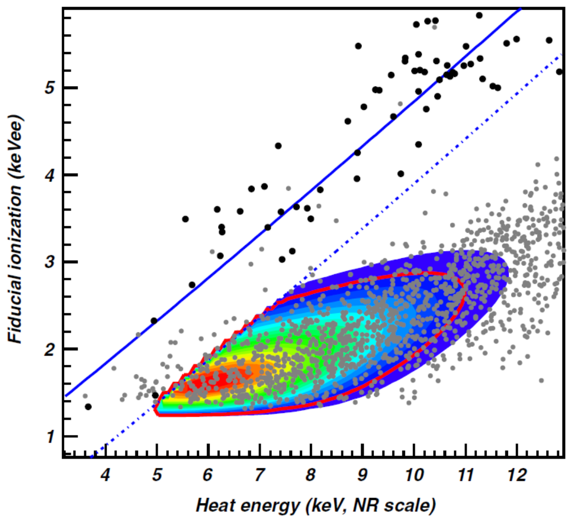

Figure 4: Map of signal density $\rho(E_r^{(h)}, E_i)$ as a function of recoil energy E_r and ionization energy E_i. The map is calculated for a 10-GeV WIMP in one of the detectors. The red line indicates the region of 90% signal strength. The black dots representing the background in the data run are above the 95% γ-ray rejection cut indicated by the dashed blue line [10]. Grey dots represent neutron calibration events.

3 Status and prospects with EDELWEISS-III

Since the end of EDELWEISS-II data taking, the experimental setup has been improved for better sensitivity in the third stage of the project. The changes concern all aspects of the experiment and are summarized below:

- The new setup contains 800-g FID bolometers with an increased fiducial volume of about 600 g. Compared to the previous 400-g ID detectors, the fraction of fiducial volume is increased from 40% to 75%. First test measurements have started with 15 bolometers and the number will increase to a total fiducial mass of 24 kg with 40 units, expected to be running by the end of 2013. Test measurements with a ^{133}Ba γ-source have confirmed that the rejection of γ-rays has improved with the new design as expected (figure 5).

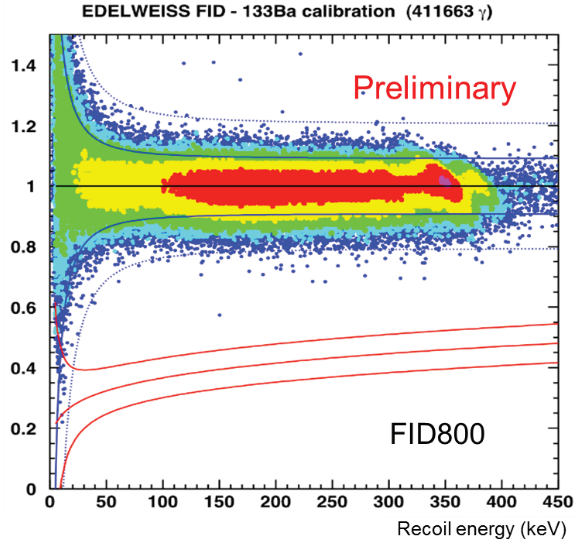

Figure 5: Ionization yield versus energy for events from a ^{133}Ba γ-source recorded with the new FID-800 detectors. Above 10 keV no events are found in the nuclear recoil band limited at 90% C.L. by the upper and lower red lines.

- The cryostat has been upgraded internally and the bolometers have been rearranged. With new thermal shields the intrinsic γ-ray contamination has been reduced significantly. A new polyethylene shield inside the cryostat and the replacement of the cables with less radioactive types will also reduce the ambient neutron rate. In addition, the rate of muon-induced neutrons is reduced by the addition of extra modules to the muon veto system. The effect of these changes is shown in Table 1: the background level is reduced for γ-rays by a factor 2–6 and for neutrons by more than 10.

Background (20 – 200 keV)	EDELWEISS-II (evt kg^{-1}day^{-1})	EDELWEISS-III (evt kg^{-1}day^{-1})
γ-rays	82	14 - 44
ambient neutrons	below 8.1×10^{-3}	(0.8 - 1.9)$\times10^{-4}$
μ-ind. neutrons	below 2×10^{-3}	below 2×10^{-4}

Table 1: Background rates achieved with EDELWEISS-II compared to the expectation with EDELWEISS-III (from [11]).

- The analog front-end electronics have been upgraded, i.e. the feedback resistors of the charge sensitive preamplifiers have been replaced by relays providing a periodical short cut. This technique reduces the electronic noise, and an energy resolution better than 1 keV (FWHM) has been achieved.

- A new DAQ system comprising the readout of up to 60 bolometers in an integrated 19" crate has been constructed (see figure 6). It integrates the timing from the muon veto and provides scalability with a higher number of detectors for future operation. The new design reduces the continuous data flow processed by Mac computers for triggering and data storage. It is possible to implement trigger algorithms in programmable gate array (FPGA) logic within the crate to reduce the processing load of the Macs even further. Options to increase the sampling speed from 100 ksamples to 40 Msamples on the ionization channels with additional electronics daughter cards are currently under investigation. A higher time-resolved recording of the ionization signal would improve the discrimination power between bulk and surface events [4].

- New analysis tools for monitoring and data analysis have been developed to handle the increased data volume [12].

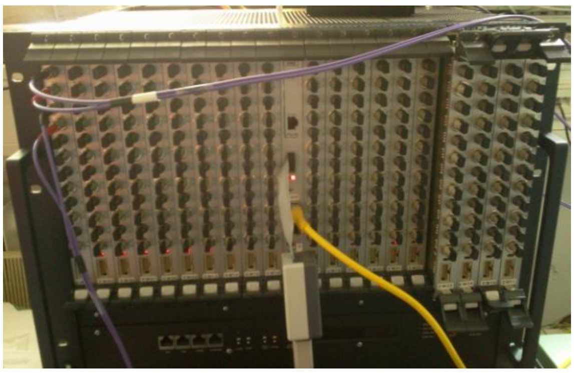

Figure 6: Photo of the new DAQ electronics: The system consists of 20 front-end modules each processing the signals from 3 bolometers, and a readout module (in the center) for generation of a central trigger and with a PCI Express (PCIe) interface.

The goal of EDELWEISS-III is to start with a commissioning run in autumn 2013. It is planned to acquire an exposure of 3000 kg·day within the first half year of operation, corresponding to a WIMP-nucleon scattering cross-section sensitivity of 5×10^{-9} pb (see bold dashed line in figure 3), and to reach a sensitivity of a few 10^{-9} pb after two years of operation. The expected background for such an exposure is less than one event.

The construction of EDELWEISS-III – which is fully funded – paves the way for the EURECA project where bolometers of multiple target nuclei with a total mass of up to 1000 kg are placed in a big cryostat [13]. EURECA is a project proposed by several European groups from France, Germany, UK, Russia, Ukraine, Spain and Czech Republic, and the CDMS collaboration has also expressed their interest in participation. This next generation experiment aims to probe WIMP-nucleon cross sections down to 10^{-11} pb (see figure 3) at a background level after cuts of 10^{-3} evt kg^{-1} year^{-1} [14].

Acknowledgment: The EDELWEISS project is funded in part by the German ministry of science and education (BMBF) within the Verbundforschung Astroteilchenphysik (grant 05A11VK2), by the Helmholtz Alliance for Astroparticle Physics (HAP) funded by the Initiative and Networking Fund of the Helmholtz Association, by the French Agence Nationale de la Recherche under contracts ANR-06-BLAN-0376-01 and ANR-10-BLAN-0422-03), by the Science and Technology Facilities Council (UK) and the Russian Foundation for Basic Research (grant No. 07-02-00355-a). We gratefully acknowledge the help of the technical staff of the Laboratoire Souterrain de Modane and the participant laboratories.

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