Improvements of the muon veto system efficiency for the EDELWEISS-III experiment

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Abstract

EDELWEISS (Expérience pour Détecter Les Wimps En Site Souterrain) is a direct detection dark matter experiment searching for Weakly Interacting Massive Particles (WIMPs) thanks to cryogenic germanium detectors (called bolometers) which allow double measurement of heat and ionization signals. The new phase of the experiment EDELWEISS-III, currently in commissioning, aims to reach a sensitivity at least 10 times better than the previous phase. In this context, it is necessary to further reduce all sources of background, notably neutron background induced by cosmic muons, rejected using a muon veto system. The studies performed to improve the efficiency of this system are described below.

1 Introduction

Since 1933 [1], many observations at different scales in the Universe state that baryonic matter represents only a tiny part of the mass-energy density of the observable Universe. Therefore in the seventies the concept of dark matter, a matter which neither emits nor reflects electromagnetic radiation and which is made up of unknown particles, was introduced. Recently, more precise measurements performed by the space telescope Planck state that the energy content of the Universe is made of only 4.9% of baryonic matter against 26.7% of dark matter whereas the rest is dark energy [2].

Despite its successful description of the subatomic world hitherto, the Standard Model of particle physics is not able to explain some observations such as dark matter or dark energy. Many theories were developed to explain the observations, giving birth to a zoo of potential candidates for dark matter. The most promising generic class of particles to make up for dark matter is the WIMP. This dark matter candidate is being tracked down by many experiments using different strategies and technologies such as the direct detection experiment EDELWEISS. The aim of EDELWEISS is to detect the scattering of a WIMP from the Milky Way galactic halo on a nucleus of a germanium detector to verify the existence of WIMP. The probability such a collision happens is very low with current experimental constraints approaching to a WIMP-nucleon cross-section of 10^{-45} cm^2 corresponding to 1 event per year in 300 kg target mass [3]. Therefore the main challenge of direct detection experiments is to avoid that background particles interact within the detectors. Hence the detectors are protected from background by several layers of shielding made of polyethylene (PE), lead or copper, and placed in an underground laboratory. EDELWEISS is operating in the underground laboratory of Modane, the deepest in Europe with a rock cover of 1700 m. This natural shield allows to stop cosmic rays except muons whose flux is nevertheless reduced by a factor 10^7. Most of the remaining background reaching the detectors can be eliminated using a double measurement of the energy deposit. Indeed, thanks to simultaneous measurement of heat and ionization, electron recoils can be distinguished from nuclear recoils. However, it is not always possible to discriminate nuclear recoils induced by neutrons from nuclear recoils induced by WIMPs. These neutrons either come from ambient radioactivity or are induced by cosmic muons. Neutron background from the radioactivity is reduced via material selection and shielding and is estimated from simulation. Muon-induced neutrons are tagged using a muon veto system. A schematic view of the EDELWEISS experiment is presented in figure 1.

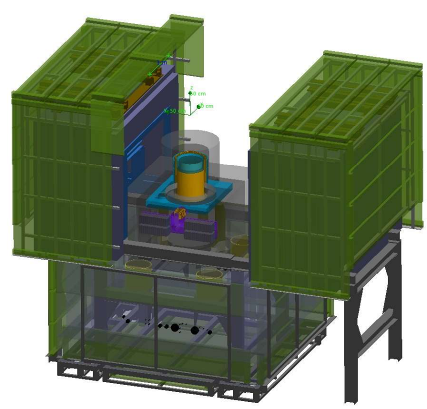

FIGURE 1: Schematic view of EDELWEISS with in green the muon veto system which surrounds the experiment

In 2011, the results of the second phase of the EDELWEISS experiment (EDW-II) were released, allowing to set new constraints on the WIMP-nucleon scattering cross-section, excluding at 90% C.L. a cross-section down to 4.4×10^{-44} cm^2 for a 85 GeV/c^2 mass WIMP. Currently, the new phase of EDELWEISS (EDW-III) is in commissioning and should start in the coming months. Its goal is to increase by at least a factor 10 the sensitivity of the second phase. For this purpose, the fiducial detection mass will be increased from 1.6 kg to 24 kg by increasing the size and the number of bolometers. In parallel, to decrease the background level, a new PE shield was installed inside the cryostat very near the detectors and 4 additional muon veto modules have been installed. In addition, a better discrimination of the residual background should be achieved by a new cryogenic structure and new electronics. Concerning the muon veto, the goal is to improve its efficiency, or at least to maintain it. The work performed or ongoing to achieve these goals is described in these proceedings.

2 The muon veto system

The muon veto system acts as an active shield to tag neutron events in bolometers, which can be attributed to a muon passage. As shown in figure 2, it is made of 46 plastic scintillator modules placed almost hermetically around the outer polyethylene shielding, covering a surface of 100 m^2. It is divided into 2 levels : an upper level called Niveau 1 made up of 30 modules and a lower called Niveau 0 composed of 16 modules. Each module is labelled by a number, from 1 for the easternmost module of the top to 48 for the southernmost module of the bottom. All of them have a width of 65 cm, 5 cm thickness with lengths of 2 m, 3.15 m, 3.75m or 4 m. In order to reach the cryostat containing the bolometers, the upper level is positioned on rails and can be opened into two symmetric parts. The modules labelled M7, M8, M15 and M16 were added in 2010 in the context of the upgrades towards EDW-III to cover the gap between the 2 chariots. More information about the muon veto system can be found in [4].

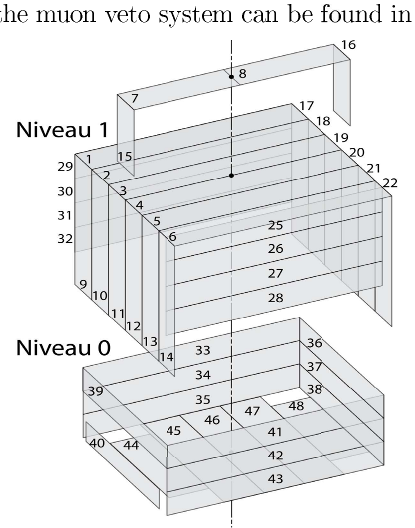

FIGURE 2: Schematic view of the muon veto system during EDW-III

When a muon crosses a module, it loses energy mainly via ionization according to the Bethe-Bloch formula. Ionization and excitation of electrons of the material induce emission of scintillation light, which propagates towards the module ends where two groups of 4 photomultipliers (PMTs) produce a signal proportional to the energy deposit. Each group of PMTs is supplied individually with high voltage (HV). The released muon energy is derived by summing the energy deposit in both PMT groups. In addition, by taking the difference of the arrival time of the signal at each module end, the position of the muon interaction along the module axis can be reconstructed. As we deal with long modules up to 4 meters, the effects of light absorption within the module are significant. Therefore the light output depends on the interaction position along the module axis. Indeed, the measured energy for a given PMT group is maximal when the interaction occurs near the PMTs and decreases roughly exponentially with the distance to the PMT group. By summing the two PMT group contributions, the effective light output is the lowest for the center of the module and rises toward the module ends. This effect combined with the triggering threshold and the triggering condition leads to a position-dependent module response. To avoid a too high dead time due to event recording, a trigger threshold of 150 mV is set on the amplitude of the two signals of a module. When both pass the threshold in a coincidence window of 100 ns, all the energy deposits in the muon veto system are stored to disk. The threshold for each module is adjusted by tuning the HV for individual PMT groups to be as low as possible without increasing the dead time. Therefore, individual modules have different effective thresholds.

The muon veto detection efficiency was derived from EDW-II data using two independent methods giving consistent results : using data from high energy bolometer events induced by muons or using a detailed MC simulation of the experiment including the modular trigger efficiencies. The first method gave a lower limit on the muon veto detection efficiency of 93.5% entirely limited by statistical uncertainties. The second method provided an efficiency of 97.7%$\pm$1.5% of detecting muons that may produce secondaries near or inside the cryostat (i.e muons crossing a sphere of 1 m radius centred on the cryostat). Thus, despite the numerous gaps due to mechanical constraints, the system rejects successfully most of the muon-induced background. For the EDW-II exposure of 384 kg.d, an upper limit of 0.72 (at 90% C.L.) muon-induced WIMP-like events in bolometers was derived, corresponding to less than 20% of the total background contribution [5].

Although the muon-induced background was not limiting the sensitivity of EDW-II, it could become problematic in the new phase with the increase of exposure and the reduction of neutron background from radioactivity. In addition to the installation of new modules, several studies have been performed to maintain and improve the muon detection efficiency.

3 Muon veto detection efficiency

3.1 Effects of the new cryogenic system

In October 2012, as part of the ongoing upgrades towards EDW-III, a new cryoline going from the cryostat through the muon veto to the thermal machines was installed. Since the cryoline has a larger diameter compared to the previous one, the muon veto can not be closed as well as previously, i.e. the gap between the two movable parts of the Niveau 1 is bigger. The extra-top modules M7, M8, M15 and M16 (see figure 2) cover part of this gap. However, these modules have some inefficiency. Therefore, by increasing the size of the gap, there is a higher probability that a muon goes through the gap between the chariots without being detected in an extra-top module, leading to a decrease of the total muon veto detection efficiency. These muons are especially dangerous because they can induce secondary neutrons in the detectors. Moreover, on the North and South sides of the muon veto (between M11 and M12 and between M19 and M20), the gap is not completely covered by the additional extra-top modules. Therefore the increase of the gap size can lead to a loss of muon detection efficiency. The aim of this work was to get an estimation of this efficiency loss.

This study is based on the analysis of muon veto data only and concentrates on the detection loss of muons coming from the top (i.e. the study concerns muons crossing the horizontal extra-top modules M7 and M8). To get the efficiency loss, the number of muons going through the gap was compared for three different sizes of the gap. To get this information, the number of muons which cross the extra-top modules M7 or M8 but neither the top module M3 nor the top module M4 is calculated from the data. By fitting with a linear function the efficiency of the top modules to detect muons crossing the extra-top modules versus the gap size, an average efficiency loss per cm of $1.0 \pm 0.2\%$ was derived.

From this result, an estimation of the additional muon-induced WIMP-like events in the bolometers due to the enlarged gap can be calculated. For this purpose, the projected rate for EDWIII of unvetoed WIMP-like events in the bolometers is used considering a muon veto efficiency of 97.7% [5]. Note that this estimation of the muon veto efficiency does not include the extra-top modules. The enlarged gap of 3.2 cm leads to an efficiency loss of 4.5% for top modules to detect muons crossing extra-top modules. The probability for a muon going through the gap to be detected in another module of the muon veto system can be approximated to the conservative probability of 75%. In this case, 1.2% of the muons would be really missed in absence of extra-top modules, providing an additional WIMP-like background of 0.3 events for an exposure of 3000 kg.d, i.e. an increase of 50%. Considering that the extra-top module efficiency is 90% (average module efficiency), the enlarged gap leads to an increase of 5% of the unvetoed WIMP-like events in the bolometers. This is a conservative estimation, thus we can conclude that the enlarged gap will not have a critical effect on the muon veto detection efficiency. Nevertheless, in order to estimate precisely the loss of muon detection efficiency of the muon veto system taking into account the extra-top modules, detailed Monte-Carlo simulations will be performed.

3.2 Compensation of module ageing

Since the installation of the muon veto in 2005, the plastic modules as well as the PMTs are ageing. As a consequence, a decrease of the light output might be observed due to oxidation of the scintillating molecules or to an increase of the light absorption within the module. In addition, PMT ageing induces a decrease of the signal amplification within the PMTs because of the less tight PMT vacuum.

Ageing effects are inhomogeneous and unpredictable. They are responsible for a loss of muon veto detection efficiency at low energy as they induce an increase of the effective modular threshold. However, the muon-candidate detection efficiency is not significantly affected by the threshold increase. Indeed, the muon average energy deposit is above 10 MeV whereas the threshold is around 5 MeV at the center, increasing towards the module ends due to the position-dependent light output. Nevertheless, the threshold increase reduces the detection of secondaries produced in the rock by muons, as well as muons depositing a low amount of energy as crossing the module edge (so-called grazing muons). However, the best muon veto efficiency should be ensured to achieve the highest sensitivity for dark matter detection, notably by extending the muon veto detection efficiency even to muons passing nearby the muon veto by detecting their secondaries. Therefore, correction of these ageing effects is necessary and can be performed by increasing the HV applied to the PMT groups.

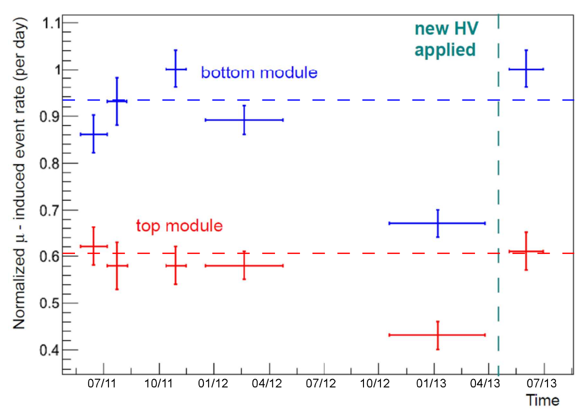

FIGURE 3: Normalized muon-induced event rate over a two year time period

Only the 4 newest modules are equipped with LEDs allowing to follow directly the ageing. However, muon-induced events can also be used to determine ageing effects. By comparing the response of each PMT group within a module, the homogeneity of the PMT group response can be tested. In addition, as modules of the same length, orientation and face have a similar behaviour and thus can be grouped, comparing muon-induced events within a group of modules allows to detect modules with outstanding response.

Muon-induced events (throughgoing muons as well as muon-induced showers) are selected by requiring at least two non-adjacent modules to be in coincidence. Then, for each module of the muon veto system, the energy distributions measured by each PMT group as well as the distribution of the position of the interaction along the module axis were checked. As expected from a homogeneous module, the mean energy of the 2 groups of PMTs should be roughly equal and the position distribution should be relatively flat. In addition, the number of muon-induced events within a module as well as the mean energy deposit should be comparable to the ones of the modules from the same group. If these conditions are not fulfilled, the HV increase which should be applied to correct for the inhomogeneous behaviour is estimated.

From this analysis, a new set of HV was derived and applied, with 40% of the HV values increased by 10 V in average. The effects of the new HV setting can be seen in figure 3. It shows the normalized muon-induced event rate versus a time period of 2 years for two modules of the muon veto system. A decrease of the rate can be seen from July 2011 to April 2013. After the new HV setting was applied, the rate is back to the value reached during the last data taking in 2011.

3.3 Deriving the module response at low energy

To achieve a better knowledge on the muon-induced neutron background in the detectors for EDW-III and thus reach a better sensitivity for dark matter search, the uncertainties on the muon veto efficiency determination should be reduced. Two methods, mentioned in part 2, can be used to define the muon veto detection efficiency. Uncertainties of the method based on bolometer data are purely statistical and will be reduced by a longer exposure, whereas uncertainties on the simulation-based method are due to a lack of knowledge of the module response at low energy, more precisely of the threshold. The goal of this work is to have a better knowledge of the module response at low energy to derive a more realistic and more precise muon veto detection efficiency, not only corrected by using an averaged threshold over all hit positions but a position-dependent threshold.

A calibration campaign was thus started with a weak AmBe source, usually used as a neutron source as it produces 20 neutrons per second of energy up to 10 MeV. In our case, the source is used as a gamma source as the neutron emission is followed in 59% of the cases by the emission of a mono-energetic gamma of 4.4 MeV. These gammas allow probing the module thresholds.

Calibration data are taken putting the source at 3 different positions along the module axis (at the module center and at 50 cm from each module extremity) for roughly 2 days for the center position and 5 days for the side positions. For each calibration, a MC simulation of the same experimental set-up is performed with the software Geant4. The module response is then derived comparing simulated and real energy spectra. The main difficulty is to understand and reproduce the module response by identifying the physical and acquisition system effects, which are not taken into account in the simulation. First, a time cut in the simulation is applied to reproduce the integration window to get the energy deposit in the acquisition system. Then, neutron energy deposit from simulation is quenched according to Birk's law since for equal energy deposit, a neutron will produce less scintillation light than a gamma. Following that, the energy resolution is implemented by randomizing the energy deposit according to a Gaussian distribution of width σ_0. Another data acquisition effect which has to be taken into account is the effective energy threshold, which is a continuous function from 0% to 100% smeared by the energy resolution. The energy threshold E_{thr} is defined as the value for which the module efficiency is 50% and highly depends on the position along the module axis and on the PMT group. Both E_{thr} and σ_0 values are input parameters of the fit. The last unknown parameter is the calibration coefficient C_{cal}, relating the simulated energy spectrum in units of MeV to the measured energy spectrum in ADC channels. To summarize, the module response is characterized by a set of 3 parameters : the energy resolution σ_0, the energy threshold E_{thr} in MeV and the calibration coefficient C_{cal} in MeV per ADC channel. After implementation of these effects in the simulation, statistical tests allow to find the best set of parameters to match the simulation and the data. The next step is to implement the position-dependent light output.

4 Conclusion

The work presented in these proceedings will lead to a more precise determination of the muon veto detection efficiency. Also simulations of muon-induced events in bolometers will be soon performed with the new EDW-III set-up, notably the additional muon veto modules and the new PE shield. Thus, the muon veto detection efficiency will be derived and the muon contribution to single scatter neutrons in the bolometers will be compared to the contribution of neutrons from radioactivity. As a final result, a first estimation of the muon-induced WIMP-like background for EDW-III will be determined.

References

[1] F. Zwicky, Helv. Phys. Acta 6, 110-127, (1933)

[2] R. Leonardi et al., arXiv : 1303.5062 [astro-ph], (2013)

[3] H. Araujo, B. Edwards et al., arXiv : 1310.8214 [astro-ph], (2013)

[4] A. Chantelauze,PhD thesis, Université Clermont-Ferrand, (2009)

[5] B. Schmidt et al., Astropart. Phys. 44, 28-39, (2013)

[6] E. Armengaud et al., Phys. Lett. B 702, 329-335, (2011)