УДК 524.78

C. Nones
(on behalf of the EDELWEISS collaboration)

CEA Saclay, DSM/IRFU/SPhN, Gif-sur-Yvette, France

THE BOLOMETRIC WAY TOWARDS THE DIRECT DARK MATTER DETECTION: THE EDELWEISS EXPERIMENT AND THE EURECA PROSPECT

Within the current cosmological concordance model, a large fraction of the mass in the universe is made of dark matter. One tool to detect dark matter in the form of WIMP is given by the direct detection. The EDELWEISS experiment, operated in the Frejus laboratory in a low-background environment, uses cryogenic germanium detectors to look for a direct search of WIMP. These detectors are subject to constant improvement with respect to the rejection capabilities against non WIMP interactions. We present here the results of a WIMP search carried out with ten so-called InterDigit detectors, technology that enables a high level of gamma radioactivity rejection within a controlled fiducial volume. A cross-section of $4.4 \cdot 10^{-8}$ pb could be excluded for a WIMP mass of 85 GeV. We also report the search for low-energy WIMP-induced nuclear recoils for an exposure of 113 kg · d. The status of the EDELWEISS-III project, which will operate 40 newly-designed FID detectors in an upgraded installation, will be given as well as a short presentation of the EURECA project aiming to a cross-section of 10^{-10} - 10^{-11} pb.

Keywords: dark matter, WIMP searches, cryogenic Ge detectors, the EDELWEISS experiment.

1. Introduction

One of the key ingredients for the current cosmological concordance model is the existence of a dark, matter-like fluid ruling the dynamics of structures from the current galactic scales to the largest scales at early cosmic times. Weakly Interacting Massive Particles (WIMP) are a generic class of dark matter particles with particularly appealing features. They appear in several extensions of the current Standard Model of particle physics, where thermal production mechanisms for such particles in the Big Bang naturally yield the order of magnitude for the observed cosmic abundance [1]. A vast effort is currently dedicated to the direct detection of WIMP from the Milky Way halo through the coherent elastic scattering on nuclei constituting a terrestrial detector. A roughly exponential nuclear recoil (NR) spectrum is expected with typical energies of a few tens of keV. Theoretical models predict a wide range of WIMP-nucleon scattering cross-sections. Current searches are approaching sensitivities for rates of a few 10^{-3} evts/kg/day, corresponding to cross-sections for spin-independent interactions at the level of a few 10^{-8} pb. Since we are dealing with very rare event searches, the dedicated detectors must therefore achieve a low energy threshold combined with high background rejection capabilities.

Although several constrained WIMP models point out to WIMP masses $M\chi$ ~100 GeV, lighter fermions with masses down to ~2 GeV are possible [2, 3].

2. The bolometric technique and the EDELWEISS experiment

Bolometers are calorimeters working at low temperatures in which the energy of particle interactions is converted into phonons and measured via a temperature variation. These thermal detectors measure the portion of the deposited energy converted into phonons and guarantee a better intrinsic energy resolution. Nevertheless they are slow detectors so that they are suitable only for experiments working at low rates. Bolometers consist of two main components: an energy absorber, where particles deposit their energy and a sensor, which converts the excess phonons produced by the particle into a signal.

The EDELWEISS experiment [4] is a direct WIMP search experiment, where nuclear recoils induced by collisions with WIMP from the galactic halo are detected using germanium bolometers working at very low temperatures (20 mK) with the simultaneous measurement of ionization and phonon signals. The comparison of the two signals makes possible to separate on an event-by-event basis the nuclear recoils from the electron recoils induced by β and γ radioactivity that constitute the major source of background in most present-day direct WIMP searches. Detectors are operated at the Underground Laboratory of Modane in the Frejus Tunnel under the French-Italian Alps. The 1780 rock overburden (4800 m water equivalent) results in a muon flux of about 5 μ/m^2/day in the experimental hall and the neutron flux above 1 MeV is 10^{-6} $n/cm^2/s$ [5].

In the next two sub-sections detectors and their improvement in time will be given.

2.1. EDELWEISS-II: ID detectors

Given the experience acquired with EDELWEISS-I [5], a new design for the detector was required. The new-generation detectors called ID (InterDigit) are essentially a variation of the coplanar grid technique, in which interleaved concentric strips are substituted for the classical disk-shaped collection electrodes. The depth of an event relative to the surfaces can be inferred from a comparison of the ionization signals on the different strips, making possible a rejection of energy deposits at the detector surfaces [6]. The EDELWEISS-II phase consisted of ten hyperpure germanium crystals of cylindrical shapes with a diameter of 70 mm and a height of 20 mm with a mass in the range 360 - 410 g. The detectors are in individual copper casings, stacked in towers of two to three ID detectors. During the entire data-taking periods, the dilution refrigerator maintains the detectors at a stabilized temperature of 18 mK. A total effective exposure of 384 kg · d has been achieved and results on WIMP search will be given in Section 4.

2.2. EDELWEISS-III: FID800 detectors

To go beyond the EDELWEISS-II sensitivity and to be competitive with other experiments, a third phase of this experiment is foreseen. The EDELWEISS-III project consists in an upgrade of both the current EDELWEISS setup and detectors. The main goal is to reach a sensitivity to WIMP-nucleon cross-section of the order of $5 \cdot 10^{-9}$ pb in a short term requiring an exposure of 3000 kg · d. For the reduction of the β and γ backgrounds, the development of an improved detector design, named Full InterDigit (FID) has been pursued. 800 g crystals are equipped with two neutron transmutation doped (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 strongly the fiducial mass for each individual detector. In addition, simulations have shown that Compton interactions spanning the fiducial and low-field guard regions may induce fake WIMP candidates. Large-statistics gamma-ray calibration of the first FID detectors have indeed shown improved rejection performances relative to ID detectors. The plan is to install 40 FID800 detectors in 2013. Infrastructure upgrades (cabling, cold electronics, cryogenics and acquisition) are necessary to host these new detectors, to reduce microphonic noise and hence the analysis threshold, and will also reduce the neutron budget within the cryostat. In addition, an inner polyethylene shield will be installed to reduce the flux of fast neutrons coming from outside the cryostat. Fig. 1 (left) shows a picture of a FID detector: interleaved electrodes are visible on all its surface and also the NTD sensor is appreciable on the top surface. Fig. 1 (right) represents a sketch of the electric field lines inside the crystal resulting in a 75 % of fiducial volume (~ 640 g).

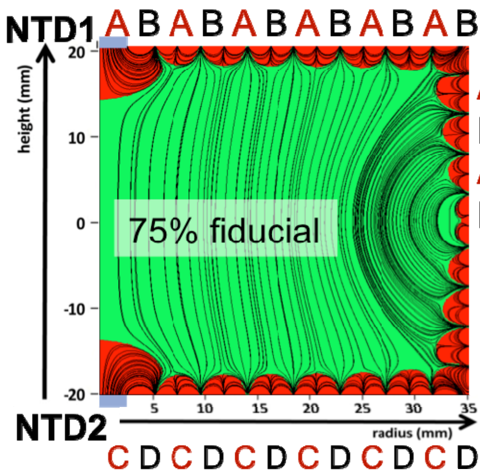

Fig. 1. *Left*: picture of a FID detector of 800 g in its copper holder. Interleaved electrodes are visible on all its surface and also the NTD sensor is appreciable on the top surface. *Right*: sketch of the electric field lines inside the crystal. (See color Figure online).

3. Final results of the EDELWEISS-II WIMP search

A WIMP search was carried out between April 2009 and May 2010 with the ten ID 400-g detectors described in Section 2.1. While all heat sensors were working correctly, a few veto or guard electrodes were malfunctioning, 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 and the recorded pulses have been then processed offline using optimal filters. Noisy periods have been rejected 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 have implied 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 [7].

The expected backgrounds are gamma and beta radioactivities, and fast neutron interactions. Summing all these background upper limits gives an estimation of 5.1 background events in the NR region for the WIMP search [8, 9]. The observed distribution shows five events in the WIMP-search region (Fig. 2, left), one at 172 keV and the other ones between 20 and 23.2 keV. Given the abovementioned backgrounds, there is no clear evidence for WIMP.

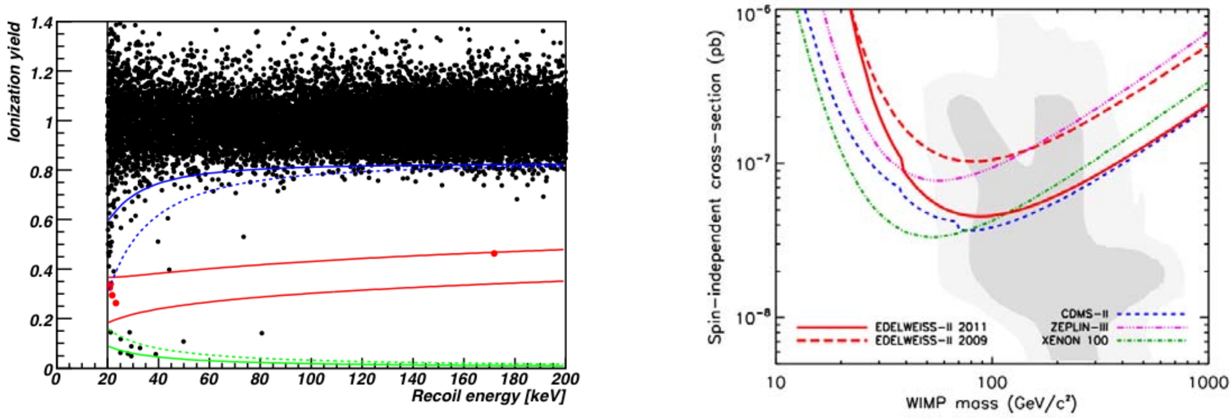

Fig. 2. *Left*: Ionization yield vs recoil energy of fiducial events recorded by EDELWEISS-II in an exposure of 427 kg·d. The WIMP search region is defined by recoil energies between 20 and 200 keV, and an ionization yield inside the 90 % acceptance band (full red lines, corresponding to an effective exposure of 384 kg · d). WIMP candidates are highlighted in red. The average (resp. worst) one-sided 99.99 % rejection limits for electron recoils are represented with a continuous (resp. dashed) blue line. The average (resp. worst) ionization thresholds are represented with a continuous (resp. dashed) green line. *Right*: Limits on the cross-section for spin-independent scattering of WIMPs on the nucleon as a function of WIMP mass, derived from the present work, together with the limits from CDMS, ZEPLIN and XENON100. The shaded area corresponds to the 68 and 95 % probability regions of the cMSSM. (See color Figure online.)

Applying the standard procedure in the field to set an upper limit in the presence of a weak, poorly constrained background, we obtain a limit on the spin-independent WIMP-nucleon cross-section of $4.4 \cdot 10^{-8}$ pb for a WIMP mass of 85 GeV. The 90 % limit as a function of WIMP mass is presented on Fig. 2 (right). This limit is degraded by the presence of the observed events at low energy.

4. Results for low-mass WIMP with the EDELWEISS-II detectors

We present here a search for low-mass WIMP using data collected by the EDELWEISS-II detectors in 2009 - 2010 [14]. The analysis optimized for WIMP masses above 50 GeV with a threshold set at recoil energy of 20 keV has already been presented in the previous section. This strategy, however, is not adequate for a search dedicated to models in which the WIMP mass is of the order of 10 GeV, for which the highest expected recoil energy is of the order of 10 keV. At this purpose we use a restricted dataset, selected on the basis of detector thresholds and backgrounds, for which low-background sensitivity to nuclear recoils down to 5 keV could be achieved. With a total exposure of 113 kg · d we find no evidence for an exponential distribution of low-energy nuclear recoils that could be attributed to WIMP elastic scattering. For WIMP of mass 10 GeV, the observation of one event in the WIMP search region results in a 90 % CL limit of $1.0 \cdot 10^{-5}$ pb on the spin-independent WIMP-nucleon scattering cross-section, which constrains the parameter space associated with the findings reported by the CoGeNT [15], DAMA [16] and CRESST [17] experiments. Further improvements in the resolution of individual channels, and in particular ionization channels, are ongoing and should allow significant progress towards background-free, low mass WIMP searches.

5. EURECA and future perspectives

EURECA (European Underground Rare Event Calorimeter Array) will aim to merge mainly the EDELWEISS and the CRESST collaborations to build a facility to house up to 1000 kg of detectors which will allow an increase of sensitivity by two orders of magnitude in the WIMP-nucleon cross-section [18]. With a shield consisting of a large water tank in which will be immersed the 1 m^3 cryostat housing the detectors, with innovative cryogenics which will rely on European expertise in the field, with adaptable cabling and electronics options, the EURECA infrastructure will be an essential tool for the community interested in the use of cryogenic detectors for dark matter searches but also for other rare event searches (Fig. 3). Beyond European detectors, it will be designed to host any type of detector, including the ones currently studied by SuperCDMS teams, following the current collaborative work performed by the two collaborations.

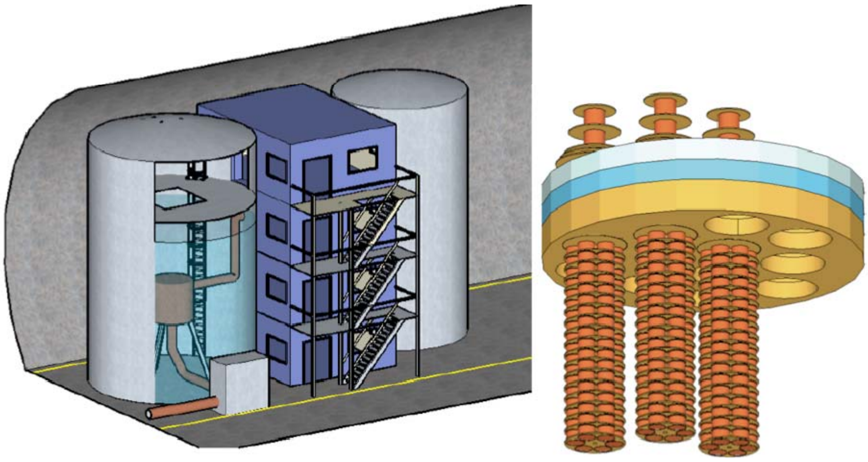

Fig. 3. Sketch of the EURECA cryostat inside a shield consisting of a large water tank. The 1 m^3 cryostat will house the detectors arranged in towers. (See color Figure online.)

EURECA will have two stages. The first phase will involve building the infrastructure, cryostat and shielding, and operating 150 kg of detectors while the second phase will be completed with 850 kg of additional detectors, the weight between the different detectors being agreed within the collaboration according to the physics reach. Thanks to a site-independent design, this infrastructure can be hosted in different locations. Such a unique facility, planned to operate over a long term, will be designed to ensure an exceptionally clean radioactive environment in order to provide the highest sensitivity in the field. A conceptual design report [19] should be considered as the first step towards construction and exploitation of that facility.

6. Conclusions

Important progresses have been done with cryogenic Ge detectors in the EDELWEISS experiment during last years. There is still a comfortable space for detector improvements including also larger masses. In addition, thanks to the big versatility of these detectors, they can be adapted to lower thresholds; at this purpose the collaboration is working on the heat channel with the development of new innovative heat sensors, called ”NbSi superconductive resistive meanders”, that have the potentiality to decrease the threshold improving also the energy resolution.

For the near future, new data in the coming year will contribute to clarify the present situation especially at low mass, a hot topic still at nowadays. In the next future, EURECA [18], a ton scale dark matter experiment, will search for WIMP interactions down to $\sigma \sim 10^{-10}$ pb corresponding to a rate of ~1 event/ton/year. It is clear that to achieve this further step different present limitations should be overcome.

This project is supported in part by the Agence Nationale pour la Recherche under contract ANR-06-BLAN-0376-01 and partly by the CEA - EUROTALENTS Programme (COW project) within the 7th European Community Framework Programme.

REFERENCES

1. *Bertone G., Hooper D., Silk J.* Particle Dark Matter: Evidence, Candidates and Constraints // Phys. Rep. - 2005. - Vol. 405. - P. 279 - 390.
2. *Lee B., Weinberg S.* Cosmological Lower Bound on Heavy-Neutrino Masses // Phys. Rev. Lett. - 1977. - Vol. 39. - P. 165 - 168.
3. *Bottino A. Donato F., Fornengo N., Scopel S.* Light Neutralinos and WIMP direct searches // Phys. Rev. D. - 2004. - Vol. 69. - P. 037302 - 037302-4.
4. http://edelweiss.in2p3.fr/

5. *Sanglard V. et al.* Final results of the EDELWEISS-I dark matter search with cryogenic heat-and-ionization Ge detectors // Phys. Rev. D. - 2005. - Vol. 71. - P. 122002 - 122002-16.
6. *Broniatowski A. et al.* A new high-background-rejection dark matter Ge cryogenic detector // Phys. Lett. B. - 2009. - Vol. 681. - P. 305 - 309.
7. *Armengaud E. et al.* Final results of the EDELWEISS-II WIMP search using a 4-kg array of cryogenic germanium detectors with interleaved electrodes // Phys. Lett. B. - 2011. - Vol. 702. - P. 329 - 335.
8. *Armengaud E. et al.* Background studies for the EDELWEISS dark matter experiment // Submitted to Astropart. Phys.; arXiv:1305.3628 [physics.ins-det], P. 1 - 15.
9. *Schmidt B. et al.* Muon-induced background in the EDELWEISS dark matter search // Astropart. Phys. - 2013. - Vol. 44. - P. 28 - 39.
10. *Ahmed Z. et al.* Search for Weakly Interacting Massive Particles with the First Five-Tower Data from the Cryogenic Dark Matter Search at the Soudan Underground Laboratory // Phys. Rev. Lett. - 2009. - Vol. 102. - P. 011301 - 011301-5; *Ahmed Z. et al.* Dark matter search results from the CDMS II Experiment // Science - 2010. -Vol. 327. - P. 1619 - 1621.
11. *Lebedenko V.N. et al.* Results from the first science run of the ZEPLIN-III dark matter search experiment // Phys. Rev. D. - 2009. - Vol. 80. - P. 052010 - 052010-14.
12. *Aprile E. et al.* First Dark Matter Results from the XENON100 Experiment // Phys. Rev. Lett. - 2010. - Vol. 105. - P. 131302 - 131302-5.
13. *Roszkowski L., Ruiz de Autri R., Trotta R.* Implications for the Constrained MSSM from a new prediction for $b \to s\gamma$// JHEP - 2007. - Vol. 07 - P. 075, 1-30.
14. *Armengaud E. et al.* A search for low-mass WIMP with the EDELWEISS heat-and-ionization detectors // Phys. Rev. D. - 2012. - Vol. 86. - P. 051701(R) - 051701-6.
15. *Aalseth C.E. et al.* Search for an Annual Modulation in a p-Type Point Contact Germanium Dark Matter Detector // Phys. Rev. Lett. - 2011. - Vol. 107. - P. 141301 - 141301-5.
16. *Bernabei R. et al.* First results from DAMA/LIBRA and the combined results with DAMA/NaI// Eur. Phys. J. C. - 2008. - Vol. 56. P. 333 - 355; *Bernabei R. et al.* New results from DAMA/LIBRA // Eur. Phys. J. C. - 2010. - Vol. 67. - P. 39 - 49.
17. *Angloher G. et al.* Results from 730 kg days of the CRESST-II Dark Matter search // Eur. Phys. J. C. - 2012. - Vol. 72. P. 1971, 1 - 22; *Brown A. et al.* Extending the CRESST-II commissioning run limits to lower masses // Phys. Rev. D. - 2012. - Vol. 85. - P. 021301(R) - 021301-5.
18. *Kraus H. et al.* EURECA - the European future of dark matter searches with cryogenic detectors // Nucl. Phys. B. - 2007. - Vol. 173. - P. 168 - 171.
19. *Angloher G. et al. (The EURECA collaboration).* EURECA Conceptual Design Report 2012, to be published.

К. Нонес
(від колаборації EDELWEISS)

БОЛОМЕТРИЧНИЙ ШЛЯХ ДО ПРЯМОГО ДЕТЕКТУВАННЯ ТЕМНОЇ МАТЕРІЇ: ЕКСПЕРИМЕНТ EDELWEISS ТА ПЕРСПЕКТИВИ ПРОЕКТУ EURECA

У рамках існуючої космологічної моделі узгодженості більша частина маси Всесвіту складається з темної матерії. Одним з інструментів для виявлення темної матерії у вигляді ВІМП-частинок (від англ. Weakly Interacting Massive Particles - слабковзаємодіючі масивні частинки) є пряме детектування. В експерименті EDELWEISS, розташованому в низькофонових умовах в лабораторії Фреджус, використовуються кріогенні германієві детектори для прямого пошуку ВІМП. З цими детекторами проводиться постійна робота з метою поліпшення характеристик, що дає змогу ідентифікувати й відкидати всі можливі події, не пов’язані з взаємодією ВІМП. У цій роботі представлено результати пошуку ВІМП-частинок, проведені з десятьма так званими детекторами InterDigit, технологією, що забезпечує високий рівень селекції гамма-радіоактивності в контрольованому чутливому об’ємі. Таким чином, можливість взаємодії ВІМП масою 85 ГеВ було виключено з даних для значення поперечного перерізу $4{,}4 \cdot 10^{-8}$ пб. Також наводяться результати пошуку за час експозиції 113 кг · доба низькоенергетичних ядер віддачі, спричинених розсіянням ВІМП, представлено поточний стан робіт у рамках експерименту EDELWEISS-III, в якому будуть використовуватися 40 нещодавно розроблених FID-детекторів в оновленій установці, а також проект EURECA з дослідження поперечних перерізів взаємодії ВІМП на рівні 10^{-10} - 10^{-11} пб.

Ключові слова: темна матерія, пошук ВІМП-частинок, кріогенні Ge-детектори, експеримент EDELWEISS.

К. Нонес
(от коллаборации EDELWEISS)

БОЛОМЕТРИЧЕСКИЙ ПУТЬ К ПРЯМОМУ ОБНАРУЖЕНИЮ ТЕМНОЙ МАТЕРИИ: ЭКСПЕРИМЕНТ EDELWEISS И ПЕРСПЕКТИВЫ ПРОЕКТА EURECA

В рамках существующей космологической модели соответствия большая часть массы Вселенной состоит из темной материи. Одним из инструментов для обнаружения темной материи в виде ВИМП-частиц (от англ. Weakly Interacting Massive Particles - слабовзаимодействующие массивные частицы) является прямое обнаружение. В эксперименте EDELWEISS, расположенном в низкофоновых условиях в лаборатории Фреджус, используются криогенные германиевые детекторы для прямых поисков ВИМП. С этими детекторами проводится постоянная работа с целью улучшения характеристик, позволяющих идентифицировать и отбрасывать все возможные события, не связанные с взаимодействием ВИМП. В этой работе представлены результаты поиска ВИМП-частиц, проведенные с десятью так называемыми детекторами InterDigit, технологией, которая обеспечивает высокий уровень селекции гамма-радиоактивности в контролируемом чувствительном объеме. Таким образом, возможность взаимодействия ВИМП массой 85 ГэВ была исключена из данных для значения поперечного сечения $4{,}4 \cdot 10^{-8}$ пб. Приведены результаты поиска за время экспозиции 113 кг · сут низкоэнергетических ядер отдачи в результате рассеяния ВИМП, представлено текущее состояние работ в рамках эксперимента EDELWEISS-III, в котором будут использоваться 40 недавно разработанных FID-детекторов в обновленной установке, описан проект EURECA по исследованию поперечного сечения взаимодействия ВИМП на уровне 10^{-10} - 10^{-11} пб.

Ключевые слова: темная материя, поиск ВИМП-частиц, криогенные Ge-детекторы, эксперимент EDELWEISS.

Надійшла 28.05.2013
Received 28.05.2013