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Dark Matter search with the CUORE-0 experiment

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Introduction

Last decades of astronomical and cosmological observations tell us that our knowledge of the Universe covers a minimum part of it: the Standard Model of particle physics describes only the 5% of the overall energy density components. The largest part, that accounts for the 68% of the total, seems to consist in the so-called Dark Energy, an unknown form of energy introduced to explain the accelerated expansion rate of the Universe. The remaining 27% appears to be made of non-baryonic and non-luminous matter, that for this reason is named Dark Matter.

Among all the possible candidates, the Weakly Interacting Massive Particles (WIMPs) are the today most favored to explain the Dark Matter nature. The strategy for their direct detection is based on the observation of the nuclear recoil produced by an elastic scattering between a WIMP and an atom of a target nucleus. Given the very low expected interaction rate, this search is performed with low-background detectors located in underground laboratories. A powerful tool that can be exploited in this research field is the signal annual modulation, which is due to the non constant relative velocity between the Dark Matter halo and the Earth. The observation of this modulation would be a strong and model independent proof of the existence of Dark Matter.

Even if many experiments have excluded the DAMA allowed region, none of these is sensitive to the annual modulation effect. Consequently any additional information to solve this puzzle would be extremely useful.

The bolometric technique, which consists in cryogenic calorimetry, is a suitable approach for the detection of WIMPs interactions. The CUORE experiment, designed to the search of the neutrinoless double beta decay of ^{130}Te , will be the largest bolometric detector ever built. It will consists in 988 TeO_2 bolometers arranged in 19 towers for a total active mass of 741 kg and will start to take data by the end of 2015 in the underground Laboratori Nazionali del Gran Sasso. Thanks to the large mass and to the low energy threshold achievable, it can extend its physics potential also to study Dark Matter. A prototype of a single CUORE tower, CUORE-0, was assembled and operated since March 2013 to validate the towers production line and the analysis tools in view of CUORE. Thanks to a remarkable active mass of 39 kg, CUORE-0, which is now in the final phase of its campaign, can be considered as an independent experiment.

This Ph.D. thesis, carried out within the CUORE collaboration, is focused on the Dark Matter search with the CUORE-0 detector. All the necessary steps, starting from the trigger implementation up to the final analysis, passing through the energy calibration, the event selection and the efficiencies evaluation, have been performed for the first time for such studies with TeO_2 bolometers.

In the first part of chapter 1 evidence for the existence of Dark Matter are summarized. In the second part the most important Dark Matter candidates are presented, focusing the attention on WIMPs.

In chapter 2, after a brief overview of WIMP detection methods, the expected signal rate for the direct detection approach is evaluated and the annual modulation effect is described. In the last part of the chapter an overview of current experiments is given.

Chapter 3 is dedicated to the bolometric technique and to the CUORE-0 detector and collected statistics.

In chapter 4 the low energy trigger is illustrated. The improvements to the trigger algorithm made during this thesis work are detailed. A study is dedicated to the trigger efficiency evaluation.

In chapter 5 the analysis procedure is presented, with particular attention to the method that was developed in this work for the validation of the energy calibration procedure.

In chapter 6 the final low energy spectrum of CUORE-0 is shown and the results of the annual modulation study are discussed.

Chapter 1

The Dark Matter Problem

1.1 Introduction

First observations of presence of a large quantity of non lightening matters were reported in 1933 by the Swiss astronomer Fritz Zwicky [1]. He observed that the Coma cluster moves faster than expected. In fact using the cluster luminosity to deduce the contained quantity of matter, he discovered that the velocity of the galaxies in the cluster was too high. This observation still holds today for scales ranging from galaxies ($\lesssim 100$ kpc) to clusters of galaxies (~ 100 Mpc), only with small corrections. In all cases the mass that shines is too small to explain the total gravitational effect. To solve this problem, Zwicky proposed the presence of non visible matter, afterwards called *Dark Matter* (DM), to account for the remaining needed mass.

In the next pages, after a brief introduction to the Standard Cosmological Model, evidence for the existence of DM and some of the most important candidates will be reviewed.

1.2 Standard Cosmological Model

The current cosmological model is based on few assumptions [2]. First of all, the laws of physics are assumed to hold in all local inertial frames, an axiom known as *Lorentz invariance*. Secondly, the Copernican principle is assumed: the location of the Earth in the Universe is not special or particularly different from any other location. This, in addition to the observed isotropy of the Universe, leads to its homogeneity (*Cosmological Principle*). When combined with the further assumption that the spatial component of the metric can be time-dependent, this implies that a specific metric must be used, known as the Robertson-Walker metric:

$$ds^2 = dt^2 - a^2(t) \left(\frac{dr^2}{1 - kr^2} + r^2 d\theta^2 + r^2 \sin^2 \theta d\phi^2 \right)$$

where r , θ and ϕ are the fixed comoving coordinates of the observer, $a(t)$ is the cosmic scale factor that describes the expansion or contraction of the Universe and k is the parameter that defines the Universe curvature. The energy content of the Universe is directly connected with k , which can assume three different values: $k = -1$, hyperbolic curvature for an open, infinite Universe, $k = 0$, no curvature for a flat infinite Universe and $k = 1$, spherical curvature for a closed and finite Universe. The simplest case, $k = 0$, is the flat Euclidean space.

In any case, with the Robertson-Walker metric, the Einstein equations of general relativity simplify to the Einstein-Friedmann equations, which determine the time evolution of the cosmic scale factor as a function of the cosmological constant Λ and of the cosmic substrate density $\rho(t)$ and pressure $p(t)$:

$$\left(\frac{\dot{a}(t)}{a(t)}\right)^2 = \frac{8\pi G}{3}\rho(t) - \frac{k}{a^2(t)} + \frac{\Lambda}{3} \quad (1.1)$$

$$\frac{\ddot{a}(t)}{a(t)} = -\frac{4\pi G}{3}(\rho(t) + 3p(t)) + \frac{\Lambda}{3} \quad (1.2)$$

where G is Newton's gravitational constant. Generally one refers to the ratio $\frac{\dot{a}(t)}{a(t)} = H(t)$ as the *Hubble parameter*, which describes the expansion rate of the Universe.

It is possible to define a critical density at the present epoch t_0 that holds assuming a flat Universe ($k = 0$) with vanishing Λ model:

$$\rho_{c,0} = \frac{3H_0^2}{8\pi G}.$$

In fact this was originally intended for the determination of the Universe geometry: if $k = 1$, $\rho > \rho_{c,0}$ for a closed Universe, while if $k = -1$, $\rho < \rho_{c,0}$ for a open hyperbolic Universe. In $\rho_{c,0}$ definition only constants appear, so it is a constant itself. In particular, according to the latest results, the Hubble parameter H_0 , has a value of 67.80 ± 0.77 (km/s)/Mpc [3].

Defining the densities:

$$\Omega_m(t) = \frac{\rho(t)}{\rho_{c,0}}$$

$$\Omega_k(t) = -\frac{k}{a^2(t)H_0^2}$$

$$\Omega_\Lambda(t) = \frac{\Lambda}{3H_0^2}$$

it is possible to rewrite eq.(1.1) as (removing the explicit time dependency for simplicity):

$$1 = \Omega_m + \Omega_k + \Omega_\Lambda. \quad (1.3)$$

This means that the present total energy density of the Universe is directly linked to its curvature. So eq.(1.1), or its new version (1.3), and eq.(1.2) with

the values of Ω_m and Ω_Λ can describe the time evolution of the Universe. The latest observations indicate that the best models to describe the Universe are those with $\Omega_\Lambda \simeq 0.68$ [3].

The non vanishing value of Ω_Λ can be interpreted, in a quantum field theory framework, as the energy density of the vacuum, generally called *Dark Energy*. Its negative pressure accounts for a repulsive gravitational interaction in general relativity. As a consequence, models with a positive Ω_Λ present a slowed down expansion that can become an accelerated expansion in a later phase of the Universe. Therefore it is fundamental to determine the values of the three variables H_0 , Ω_m and Ω_Λ to understand the ultimate fate of all cosmological models with $\Omega_\Lambda \neq 0$.

1.3 Dark Matter evidence

1.3.1 Spiral galaxies

The strongest convincing observations of DM existence after the Zwicky claim in the 30's arrived in the 70's, when Rubin and Ford discovered that most of the stars in spiral galaxies orbit at roughly the same speed [4]. Assuming the gravitation model is correct, the straightforward implication is that the mass density in galaxies is constant well beyond the galactic bulge, where the largest part of the mass is seen. A spiral galaxy, such as Andromeda, consists of a central bright bulge surrounded by a rotating disk of younger stars.

Simply using Newtonian mechanics and presupposing circular orbit around the galaxy center for the stars in spiral galaxies, it is possible to estimate their rotation velocity. Using the Gauss theorem (all the mass can be assumed being in the center of the sphere with radius r) it is possible to equate the gravitational and the centrifugal forces:

$$\frac{GM(r)m}{r^2} = \frac{mv^2(r)}{r},$$

that, for the rotation velocity, leads to

$$v(r) = \sqrt{\frac{GM(r)}{r}}$$

where G is the gravitational constant and $M(r) = 4\pi \int \rho(r)r^2 dr$, with $\rho(r)$ mass density profile inside radius r . If the mass is given only by the visible components of the galaxy, outside the optical disk the velocity should fall as $\propto 1/\sqrt{r}$. The fact that, instead, the velocity is approximately constant implies that $M(r) \propto r$ and $\rho \propto 1/r^2$. An example of this behavior is given in fig.1.1, where the rotation curve of NGC 6503 is shown. The missing mass can be accounted for by the non-visible DM with a spherical density halo.

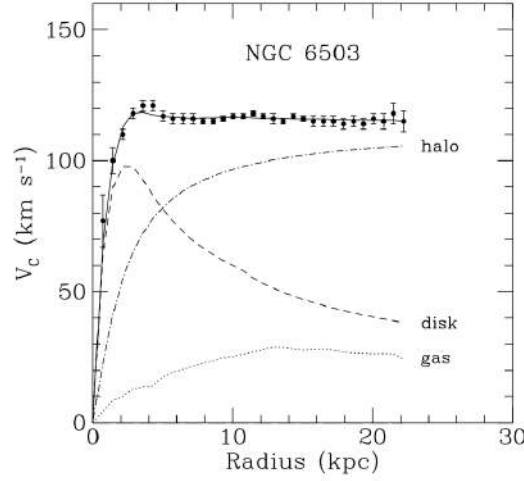


Figure 1.1: Rotation curve of NGC 6503. The dotted, dashed and dash-dotted lines are the contributions of gas, disk and dark matter, respectively. Figure from [5].

There are other convincing observations of this hypothesis: vertical velocity dispersion supports the fact that the DM cannot be contained alone in the disk, as well as material orbiting perpendicularly to the normal disk, which concludes to an almost spherical gravitational potential [6].

1.3.2 Galaxy clusters and gravitational lensing

At a much larger scale than a single galaxy there are the galaxy clusters. These are the largest gravitationally bounded structures in the Universe and consist of from hundreds to thousands galaxies to form a total mass up to 10^{18} solar masses $M_{\odot}$. They are formed from the gravitational collapse of regions of several Mpc of the early universe. As mentioned previously, it was from a galaxy cluster - the Coma cluster - that the first indication of the existence of a large amount of non visible matter in Universe arrived.

A typical variable used to describe the relative DM mass quantity in a cluster is the mass-to-light ratio, that represents the ratio between the mass and the luminosity of an object. For the Coma cluster this value is 400 solar masses per solar luminosity, two orders of magnitude larger than the solar neighborhood. Different studies demonstrated that this objects are largely dominated by non luminous matter [7].

There are three independent methods to study the mass of a cluster: application of the virial theorem to the cluster itself [8], X-ray of hot intra-cluster gas [9] and gravitational lensing [10].

The virial theorem states that in a system at equilibrium, which center is at rest, the average potential energy $\langle V \rangle$ is two times the average kinetic energy

$\langle T \rangle$, where average is meant over time:

$$2 \langle T \rangle = - \langle V \rangle .$$

Making the calculations for a cluster of N galaxies the kinetic and potential energies result to be:

$$\langle T \rangle = \frac{1}{2} N \langle m v^2 \rangle$$

$$\langle V \rangle = -\frac{1}{2} G N (N-1) \frac{\langle m^2 \rangle}{\langle r \rangle}$$

where $\langle m \rangle$ and $\langle r \rangle$ are the average mass and distance from the center, respectively. Hence the dynamic mass is:

$$M \simeq 2 \frac{\langle r \rangle \langle v^2 \rangle}{G}$$

using $N-1 \simeq N$ and $N \langle m \rangle = M$, where M is the cluster mass, which generally results larger than the luminous one.

The second way to evaluate the total mass is to measure the X-ray profiles of hot intracluster gas. In fact fitting these profiles with temperature and density distribution models, under the hypothesis of hydrostatic equilibrium, it is possible to determine the mass of the cluster. In fig.1.2 there is the comparison between the dispersion velocities of the galaxies as obtained by X-ray measurements against the dispersion velocities as obtained from weak lensing (see next point).

Finally, the gravitational lensing is based on the gravitational effect of the cluster mass on light coming from a behind source. The general relativity foreseen a deviation angle α for a light ray passing at distance r from a mass M given by

$$\alpha = 4 \frac{GM}{c^2 r}$$

where c is the speed of light. If the source, the central “bending” mass and the detector are sufficiently aligned, the observer sees a luminous ring (called Einstein ring) due to light distortion, which is tangential to the center of the gravitational potential (see fig.1.3).

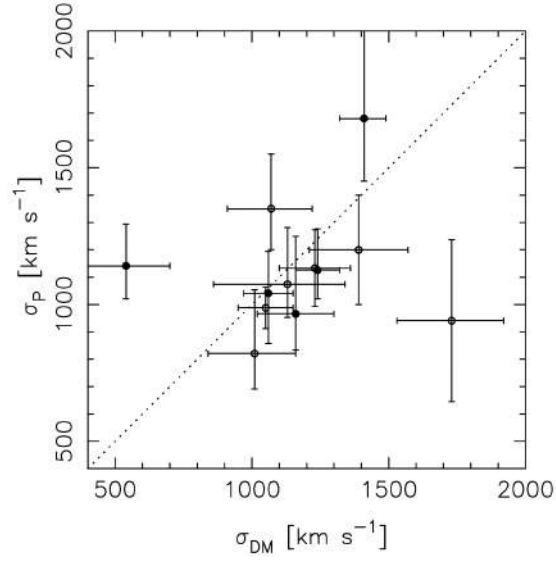


Figure 1.2: Spectroscopically measured velocity dispersion σ_P from X-ray vs DM velocity dispersion σ_{DM} from weak lensing measurements. The dotted line represent equality between the two. Error bars are 1σ . Figure from [11].

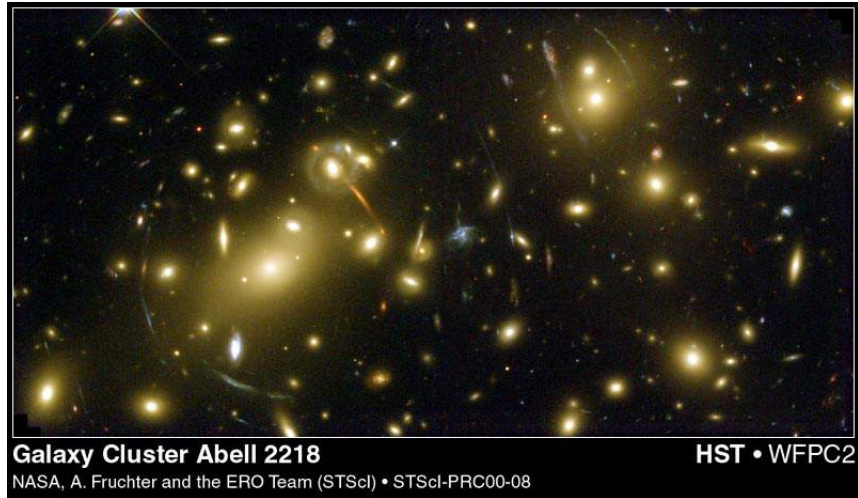


Figure 1.3: Gravitational lensing example. Giant luminous arcs and many arclets are visible. They are produced by the bending of light due to the Abell 2218 cluster mass. Image from Hubble Space Telescope.

1.3.3 The early Universe

On distance scales of the size of galaxies and clusters of galaxies, evidence of DM appears to be compelling. Despite this, the observations discussed do not permit a determination of the total amount of Dark Matter in the Universe. In subsequent sections will be shown how such information can be extracted from the study of the Cosmic Microwave Background and from the analysis of the light nuclei abundances related to the Big Bang Nucleosynthesis.

1.3.3.1 Cosmic Microwave Background

Proceeding back in time, Universe becomes hotter and denser. In the firsts 400000 years after the Big Bang, temperature was larger than ≈ 3000 K, hence atoms were not stable and matter and radiation were in thermal equilibrium. Matter existed in an opaque plasma state of ionized atoms, which strongly absorbed electromagnetic radiation of all wavelengths. After this period, temperature was low enough to allow stable atoms formation, in particular hydrogen and helium. At this point only radiation with precise wavelengths, or with sufficient energy to ionize them, was absorbed by atoms. This is called the era of decoupling of matter and radiation, since from now on the Universe is transparent to all that wavelengths carrying energies lower than the one needed for the atoms ionization.

If the Universe began in a hot and dense state, then it should be filled with a relic background of the last scatterings before decoupling. This remnant of the transparency point, at which the expanding universe dropped below about 3000 K, so that radiation could escape, should have the Planck black-body spectrum:

$$\int_0^{\infty} \frac{\nu^3}{e^{h\nu/k_B T_r} - 1} d\nu \propto T_r^4$$

where ν is the radiation frequency, h the Planck constant, k_B the Boltzmann constant and T_r the radiation temperature. This microwave radiation takes the name of Cosmic Microwave Background (CMB) which is isotropic and constant in time. The first to measure a discrepancy from the black-body radiation was the COBE (COsmic Background Explorer) satellite, which measured an anisotropy of the order of a part in 10^5 [12]. Then another satellite, the WMAP (Wilkinson Microwave Anisotropy Probe), measured this anisotropy with a 13 arcminute FWHM resolution of the sky with its onboard instrumentation. Fig.1.4 shows the temperature fluctuations of the CMB anisotropy in the full sky as measured by WMAP. The microwave background temperature fluctuations record inhomogeneities in the photon-baryon fluid at the era of last-scattering. These inhomogeneities can be seen as incoherent acoustic waves in the photon-baryon fluid of the last-scattering surface, and the densities of baryonic and non-baryonic matter have strong effects upon these oscillations: baryons increase the inertia of the oscillating photon-baryon fluid, while DM reduces the driving effect of those oscillations upon the gravitational potential.

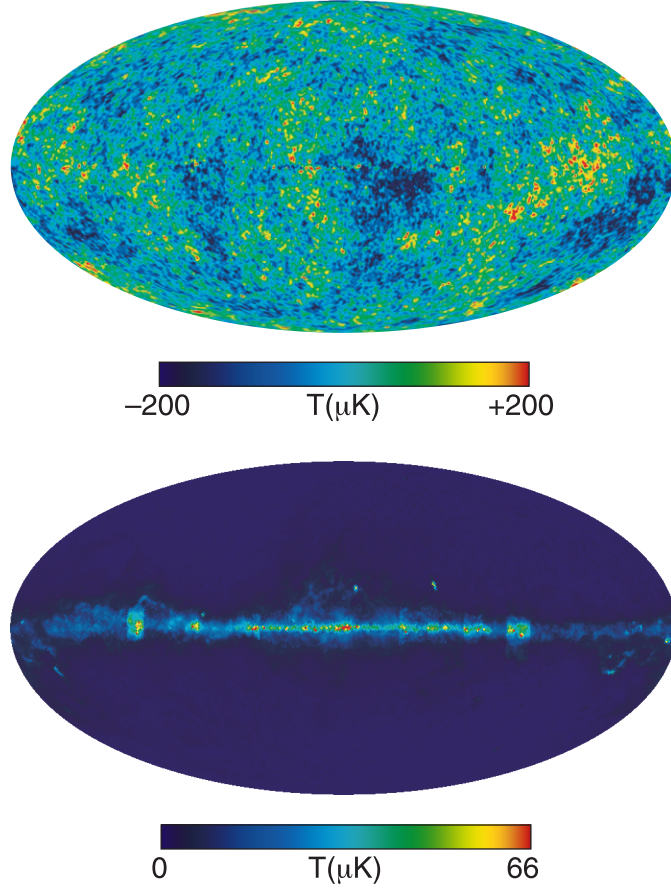


Figure 1.4: Top: map of temperature anisotropy from 9 y of measurement of WMAP. Bottom: sky map displays the part of the error in each pixel due to foreground-CMB covariance (it shows the standard deviation of expected error fluctuations, marginalizing over correlations between pixels). Figure from [13].

The observed temperature anisotropies in the sky are usually expanded as

$$\frac{\delta T}{T}(\theta, \phi) = \sum_{l=2}^{+\infty} \sum_{m=-l}^{m=l} a_{lm} Y_{lm}(\theta, \phi)$$

where $Y_{lm}(\theta, \phi)$ are spherical harmonics. The variance C_l of a_{lm} is

$$C_l \equiv \langle |a_{lm}|^2 \rangle \equiv \frac{1}{2l+1} \sum_{m=-l}^{m=l} |a_{lm}|^2.$$

Given that fluctuations seem to be gaussian, all the information contained in the CMB map can be described by the power spectrum, essentially giving C_l

as a function of l . In fig.1.5 the typical variable $l(l+1)C_l/2\pi$ is presented as a function of l , as measured from WMAP. The position of the first peak allows to evaluate Ω_k , which results to be equal to $-0.0027^{+0.0039}_{-0.0038}$ [13]. This means that Universe is flat/Euclidean (see sec.1.2). The peaks relative height of fig.1.5 probes the matter and the barion densities, which result to be respectively:

$$\Omega_m h^2 = 0.1364 \pm 0.0044 = (0.279 \pm 0.025)h^2$$

$$\Omega_b h^2 = 0.02264 \pm 0.00050 = (0.0463 \pm 0.0024)h^2$$

with numbers taken from [13]. It is evident that baryonic contribution to the total matter in the Universe is very small, even compared to the total matter quantity.

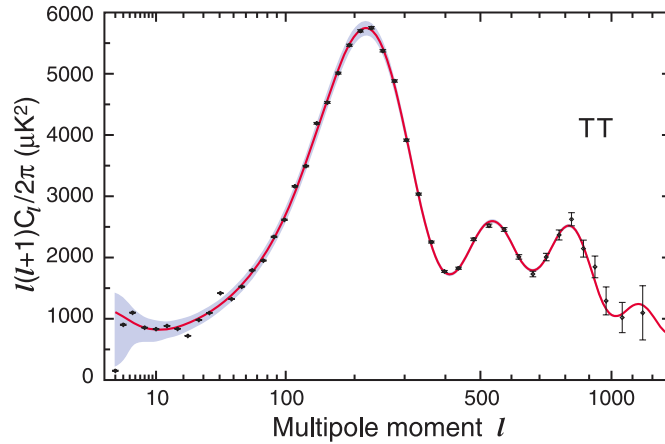


Figure 1.5: Nine year WMAP TT angular power spectrum. The WMAP data are in black, with error bars, the best fit model is the red curve, and the smoothed binned cosmic variance curve is the shaded region. The first three acoustic peaks are well determined. Figure from [13].

1.3.3.2 Big Bang Nucleosynthesis

To study nature on its largest scales, it is useful to turn to observations related to the early Universe. Studies of Big Bang Nucleosynthesis (BBN) lead to robust and independent measurements of the baryon density of the Universe, and therefore represent a cornerstone for the existence of non baryonic Dark Matter. Big Bang Nucleosynthesis is a non equilibrium process that took place over the course of a few minutes in an expanding, radiation-dominated plasma with high entropy and many free neutrons [14].

Light element abundances prediction of the Big Bang Nucleosynthesis are reported in fig.1.6.

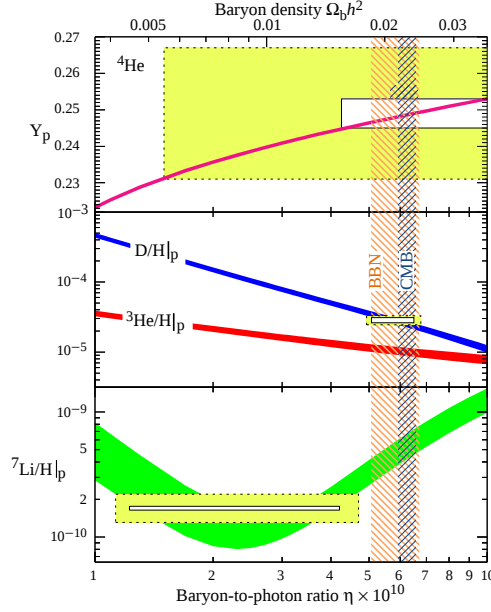


Figure 1.6: Big Bang Nucleosynthesis abundance prediction for D, ^3He , ^4He and ^7Li , the bands show the 95% C.L. range. Boxes indicate the light element measured abundance (smaller boxes: $\pm 2\sigma$ statistical errors; larger boxes: $\pm 2\sigma$ statistical and systematic errors). The narrow vertical band indicates the CMB measure of the cosmic baryon density, while the wider band indicates the BBN concordance range (both at 95% C.L.). Apart from ^7Li , there is a very good agreement between light elements. Figure from [15].

In the first 10^{-5} s of the Universe, before the QCD transition, there were roughly equal numbers of electrons, positrons, neutrinos, antineutrinos and photons. The ratio of photons to nucleons, i.e. protons and neutrons, was more than a billion to one. The nuclei had not been formed and the ratio of neutrons and protons was unity due to the weak processes that interconvert them. At about one second, when the Universe had cooled to around 10^{10} K, the weak processes were not able to keep the same number of neutrons and protons. At the temperature of $\sim 10^9$ K the first formation of D, ^3H , ^3He and ^4He took place. As the Universe continued to expand and cool, the processes maintaining equilibrium slowed down according to the temperature evolution and, after five minutes, most neutrons were “trapped” in ^4He nuclei, while most protons remained free. There was also formation, in much smaller amounts, of D, ^3He , ^7Li but the low density and temperature caused the elemental composition of the Universe to remain unchanged until the formation of the first stars a few billion years later.

The photon density sets time and interval of nucleosynthesis through its control of the Universe expansion rate; given equal photon densities, a greater

baryon density leads to a faster rate of fusion to ${}^4\text{He}$ and fewer nucleons left over in ${}^2\text{H}$ and ${}^3\text{He}$. Since the photon density is well known from the microwave background black body temperature, light element ratios thus provide an excellent “baryometer” with which to measure the abundance of ordinary matter.

Looking at fig.1.6, despite the lithium, the concordance between the elements is very good and leads to $5.1 \leq \eta \leq 6.5$ (95% C.L.), fundamentally bound by D/H. The precise measurement of deuterium is due to the fact that it has been created only once during BBN and it is easily destroyed in stars. Since the deuterium abundance is sensitive to η and decreases with time, any measurement of deuterium yields a direct upper limit on η . This provides a barionic content of the Universe of $0.019 \leq \Omega_b h^2 \leq 0.024$ (95% C.L.), that means $\Omega_b \approx 0.05$ (where Ω_b is the barionic component of eq.(1.3)). These results are compatible with the ones coming from the CMB study. Hence only a small percentage of Universe consists of the same matter we are made of.

1.3.3.3 Large scale structures

The black-body nature of CMB tells that the early Universe was almost perfectly homogeneous. The inhomogeneities seen on the radiation are due to small density fluctuation. This density contrasts are enhanced by gravitation force with time, leading eventually to the formation of galaxies or clusters if the self-gravity of an overdense region becomes large enough to decouple from the overall Hubble expansion.

Currently, the Sloan Digital Sky Survey (SDSS) is systematically mapping a quarter of the entire sky and determining the position and absolute brightness of more than 100 million celestial objects [16]. This survey measures the Universe geometry by means of the distance-redshift relation in the clustering of galaxies using the Baryon Acoustic Oscillation (BAO) [17]. Latest results drives to $\Omega_m \approx 0.3$, depending on the models and on the used set of data from various experiments [18].

In addition to direct measures, cosmologists are interested in large scale structures because they provide a unique model to refer to in the realization of numerical computer simulations of the Universe. Many N-body simulations are done based on Big Bang model. Filling the primordial Universe with different composition of elements and initial density perturbation it is possible to study its evolution in time. Hence models can be refused and parameters bounded by comparing simulation results with observations.

There are fundamentally two possible models: Hot Dark Matter and Cold Dark Matter.

Hot Dark Matter (HDM) is formed by light particles ($\lesssim 100\text{eV}$), that remained relativistic for a long time after the Big Bang. Due to particles high speed, small area region (distances below $\approx 40\text{Mpc}$) fluctuations were dumped by the streaming of energy among particles. This allow formation first of large scale structures and only in a second moment of smaller ones, like galaxies. In this *Top-down* scenario, Standard Model (SM) neutrino seem to be a possible

DM candidate. However, neutrino streaming results in very low density contrast on galactic scales, thus making galaxy formation nearly impossible [19].

Cold Dark Matter (CDM) is formed by heavy particles ($\gtrsim 1$ GeV), that freezed quite soon. These particles could decouple from the cosmic fluid much earlier than baryons and are free to cluster as soon as they become non relativistic. Differently from the HDM case there is no relevant energy exchange dumping. Consequently CDM could drove the formation of structures on a sub-galactic scale, that then grouped in larger systems (*Bottom-up* scenario).

The outcome of these numerical simulations to study large scale structure formation strongly support models with a cosmological constant $\Lambda \neq 0$ and a large fraction of non baryonic CDM [20]. HDM does not provide a good fit with observations, since essentially all small scale structures corresponding to supercluster scale or below are wiped out.

1.4 Dark Matter candidates

As seen in the previous section, the existence of DM is supported by many observations at all astrophysical scales. It is also undeniable that it represents a much larger fraction of the Universe than baryonic matter (about five times larger). Despite all of this, very little is known about the particle/s that make up the DM. The constraints that arise from observations are:

- DM must be stable, or at least with a long life time compared to the present age of the Universe;
- DM is probably only gravitationally/weakly interacting, since, despite its large amount, it is hard to directly detect and because of upper limits on self-interactions from astrophysical observations;
- DM nature is non baryonic, due to BBN and CMB observation in addition to the fact that it seems to not interact with light;
- DM is slow moving, since CDM models better reproduce the actual Universe structure and content.

There are many DM particle candidates, with masses ranging from 10^{-5} eV = $9 \times 10^{-72} M_{\odot}$ for axions to $10^4 M_{\odot}$ for black holes. There are some historical candidates, that do not fit one or more of the conditions above. Baryonic candidates, for example, are MAssive Compact Halo Objects (MACHOs) [21, 22, 23, 24], such as brown dwarfs (balls of H and He with masses below $0.08 M_{\odot}$), jupiters (masses near $0.001 M_{\odot}$), stellar back-hole remnants (masses near $100 M_{\odot}$) and neutron stars. This hypotheses has been discarded by experiments like EROS (Expérience pour la Recherche d'Objets Sombres) that put a stringent limit on their fraction in the halo composition (in the EROS case smaller than 25% [25]).

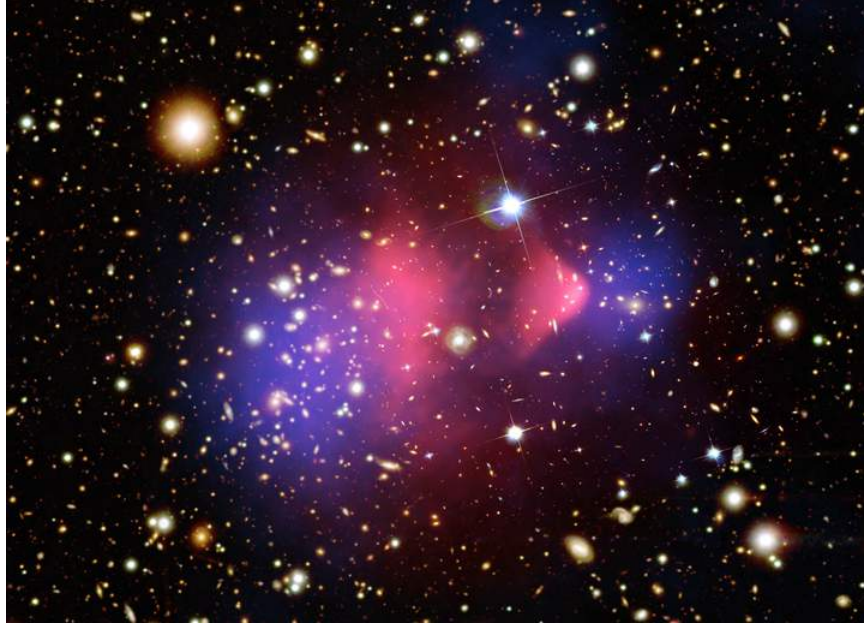


Figure 1.7: The galaxy cluster 1E0657-56, also known as the bullet cluster. Color code: X-ray from intracluster medium (accounts for the largest baryonic fraction) in Pink from Chandra telescope [28], Optical (galaxies) in White/Orange from Magellan [29] and Hubble [30] telescopes and Lensing Map in Blue. Since there are two different lens centers, one can conclude that DM is the predominant mass component of the cluster. Figure from <http://chandra.harvard.edu/>.

A possible explanation of the behaviors observed at various scale is to modify the gravitational dependency on distance, making it to decrease less rapidly than r^{-2} . This possibility has taken in consideration since Newtonian's law has never been checked at very low accelerations, as the ones due to gravity at very large distances. This theory was first introduced in 1983 by Milgrom [26] and takes the name of Modified Newtonian Dynamics (MOND). The idea is to substitute $\vec{F} = m\vec{a}$ with

$$\vec{F} = m\mu\left(\frac{a}{a_0}\right)\vec{a}$$

where $\mu(x) = 1$ for $x \gg 1$ or $\mu(x) = x$ for $x \ll 1$.

However DM existence and dominance at large scale is proved by gravitational lensing of colliding galaxy clusters. In fig.1.7 the cluster 1E0657-56 is shown, where two subclusters have collided [27]. The galaxies of two subclusters are far away each other after the interaction, being passed with no collisions.

The intracluster medium, instead, heated and left back near the interaction point, because of the collisions.

Using gravitational lensing it is possible to test the DM hypothesis. If DM is the predominant component of the subclusters, being low self-interacting, two different lens centers should be visible, near the concentration of galaxies. On the contrary if the intracluster medium is the larger component, basing on the mass-to-light ratio of galaxies and clusters explained by modified gravity, the weak lensing should show one center, near the gas.

The system mapping with gravitational lensing shows that there are two centers (the blue regions in fig.1.7), one per subcluster region, rather than only one located on the gas, where the most of baryonic matter is concentrated [27, 31]. Weakly interacting DM would move together with the galaxies, and therefore explains the observed system. There are other examples of colliding clusters of galaxies, showing all the same behavior that supports the non baryonic CDM model [32, 33]. Therefore these observations fundamentally rule out the MOND theories and provide a direct and model independent observation proof of DM existence.

In the following sections other historical candidates will be presented, focussing in particular on the Weakly Interacting Massive Particles, which are the actual most favored DM candidate.

1.4.1 Standard Model and sterile neutrinos

The unique non baryonic, massive, long living particle existing within the SM is the neutrino. SM foresees a massless neutrino, but several experimental results on oscillations require a non null mass particle [34, 35, 36, 37]. Even if they cannot be the dominant constituent of the DM, as seen in sec.1.3.3.3, they can contribute significantly to the total density. The neutrino density Ω_ν as a function of their assumed masses m_{ν_i} is given by:

$$\Omega_\nu = \frac{8\pi G}{3H_0^2} n_\nu \sum m_{\nu_i}$$

where n_ν is the actual number density of neutrinos. Neutrinos decouple from other particles at a temperature of $T \approx 1 \text{ MeV}$, when their reaction rate becomes less than the expansion rate of the Universe. At the decoupling moment neutrinos are still relativistic (masses $< 1 \text{ MeV}$) and their number density per flavor is linked to the photon density n_γ by [17]

$$n_\nu = \frac{3}{4} \frac{4}{11} n_\gamma = \frac{3}{4} \frac{4}{11} \frac{2\zeta(3)}{\pi^2} T^3 \simeq 113 \text{ cm}^{-3}$$

where $T = 2.72548 \text{ K}$ is the CMB black body temperature [38], $\zeta(x)$ is the Riemann's zeta function, the factor $3/4$ comes from Fermi statistics and the factor $4/11$ is due to the rise of n_γ by e^+e^- annihilation. The total density contribution for a Dirac neutrino (or half of this for a Majorana neutrino, see sec.3.3.1) can then be written as [39]:

$$\Omega_\nu = \frac{\sum m_{\nu_i}}{93 \text{ eV}} h^{-2}$$

Given the very low neutrino masses ($\sum m_{\nu_i} \lesssim 1 \text{ eV}$ [15]) it results that their contribution to DM density is negligible: $\Omega_\nu \lesssim 0.07$.

Sterile neutrinos are hypothetical particles similar to SM ones, with the difference that they are not weakly interacting, apart from mixing with standard neutrinos. They were proposed as DM candidates in 1993 [40]. Stringent cosmological and astrophysical constraints on sterile neutrinos come from the analysis of their cosmological abundance and the study of their decay products [41]. Sterile neutrinos could also be CDM, if there is a very small lepton asymmetry, in which case they are produced resonantly with a non thermal spectrum [42].

It is evident at this point that known SM particles are not enough to account for the full amount of DM needed in the Universe. Therefore a new, yet unknown, component of the Universe must be found expanding the current SM of particle physics.

1.4.2 Axions

Axions are hypothetical particles introduced in 1977 by Peccei and Quinn to try to solve the Strong CP Problem: strong force has been found to not violate CP as predicted by quantum chromodynamics [43]. In fact a neutron electric moment from SM calculation should be several orders of magnitude larger than the current experimental lower limit of $10^{-26} e \text{ cm}$ [44]. The theory suppose the existence of a hidden global U(1) symmetry, named the Peccei-Quinn (PQ) symmetry, which spontaneous breaking produces a new pseudo-Nambu-Goldstone boson. This particle produced by the symmetry breaking relaxes the CP violation term to zero. Hence this particle is dubbed the axion.

Axion mass is related to the PQ symmetry and is given by

$$m_a \simeq 6 \mu\text{eV} \cdot \left(\frac{10^{12} \text{ GeV}}{f_a} \right)$$

where f_a is the axion decay constant and is proportional to the vacuum expectation value which breaks PQ symmetry. Axion mass is unknown, but there are limits on f_a . The duration of the neutrino burst from SN1987A provides the limit $f_a \gtrsim 10^9 \text{ GeV}$ [45]. While the axion energy density could not be too large, otherwise the early universe would have collapsed, hence $f_a \lesssim 10^{12} \text{ GeV}$ [46, 47, 48]. This bounds the axion mass in the range that goes from μeV to meV [49]. The axion-photon coupling $g_{a\gamma\gamma}$ is proportional to the axion mass, being

$$g_{a\gamma\gamma} = \frac{\alpha g_\gamma}{\pi f_a}$$

with α fine structure constant and g_γ dimensionless model dependent coupling parameter of order 1 [50]. Axions may be created in the early Universe

as a non relativistic condensate [47]. The average axion relic density can be estimated as

$$\Omega_a h^2 \approx \left(\frac{f_a}{10^{12} \text{ GeV}} \right)^{7/6}.$$

Axion coupling to matter is extremely small, but its decay into two phonons can be stimulated by a resonant cavity and a strong magnetic field. All the axions detection techniques are based on the exploitation of this possibility.

Several ongoing experiments, such as CAST (CERN Axion Solar Telescope) [51], ADMX (Axion Dark Matter eXperiment) [52] and PVLAS (Probing Vacuum with polarized Light) [53], are trying to detect axions, with no positive results. Ongoing and future experiments are expected to probe the couplings of axions to various particles and set limits on the contribution of axions to the Dark Matter content of the Universe.

1.4.3 Weakly Interacting Massive Particles

An extremely suitable DM candidate is represented by the Weakly Interacting Massive Particles (WIMPs), generally denoted by χ . A point in their favor is that they arise naturally in many particle models, like the Supersymmetry (SUSY). These hypothetical massive particles interact only weakly and gravitationally, are non relativistic (CDM) and can be generated as a Big Bang relic with the desired density.

In the very early Universe the particles χ were in thermal equilibrium because the temperature were much higher than their mass: $T \gg M_\chi$. This reflect in a continuos process of creation and destruction: $\chi\bar{\chi} \rightleftharpoons \bar{l}l$, where $\bar{l}l$ can be quark-antiquark, lepton-antilepton pairs, Higgs and/or boson pairs, if the mass M_χ is larger than twice the masses of these particles. In an ideal gas, the number density of these relativistic particles is $n_\chi \propto T^3$. With temperature lowering, at the moment of falling below M_χ , the particles number density falls exponentially ($n_\chi \propto e^{-M_\chi/T}$) and the annihilation rate of the WIMPs $\Gamma_\chi = \langle \sigma v \rangle n_\chi$ (σ is the thermal averaged total annihilation cross section, v is the relative velocity) becomes smaller than the expansion rate of the Universe, that is $\Gamma_\chi < H$. The annihilation of the particles then becomes inefficient and a relic abundance remains (they “freeze-out”). Using the Boltzmann’s equation it is possible to evaluate the WIMPs matter contribution:

$$\Omega_\chi = \frac{8\pi G}{3H_0^2} M_\chi n_\chi \simeq \left(\frac{3 \times 10^{-27} \text{ cm}^3 \text{ s}^{-1}}{\langle \sigma v \rangle} \right) \frac{1}{h^2} \quad (1.4)$$

which approximation is independent from M_χ , and dependent only from the total annihilation cross section. In fig.1.8 are shown numerical solutions for the Boltzmann equation. The equilibrium (solid line) and actual (dashed lines) abundances per comoving volume are plotted as a function of m_χ/T , which increases with increasing time. As the annihilation cross section is increased, the WIMPs stay in equilibrium longer and the relic abundance today is smaller.

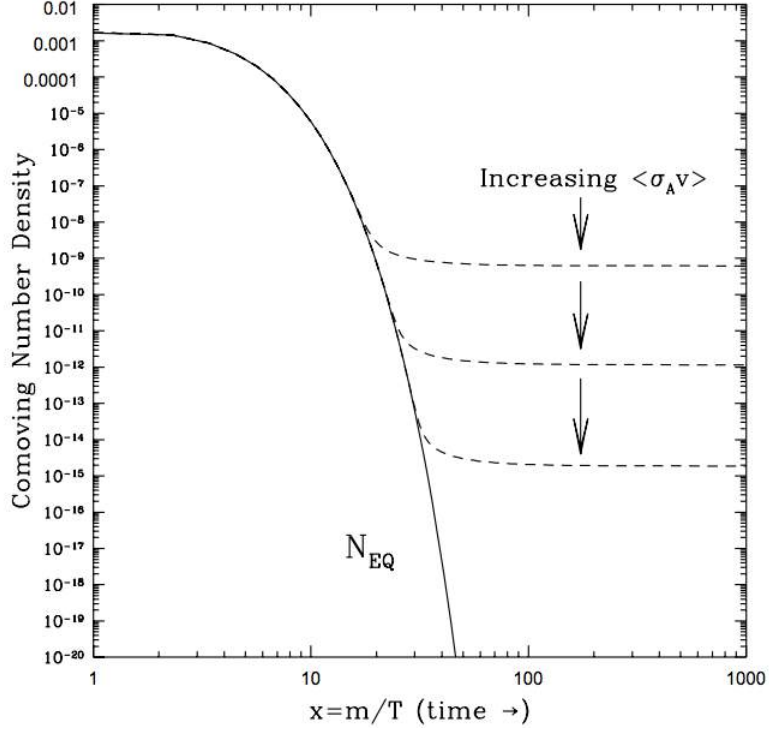


Figure 1.8: WIMPs comoving number density as a function of the temperature (in units of M_χ). Solid line represents the equilibrium, while the dashed lines represent the actual abundances for different values of $\langle\sigma v\rangle$ (velocity weighted annihilation cross section). The freeze-out occurs when the reaction rate drops below the expansion rate (for $T < M_\chi$). Figure from [54].

As discussed in the previous section, it seems that there are no solutions to the DM problem within the SM, so a new paradigm is needed. A possible solution comes from Supersymmetry, already quoted at the beginning of this section. The SUSY theory is introduced to solve the problems of the mass hierarchy of particle physics as well as to unify all the non gravitational forces towards a Grand Unified Theory (GUT). In this model, each particle is foreseen to have a supersymmetric partner. The new symmetry relates elementary particles of one spin to another particle that differs by half a unit of spin and are known as superpartners. Since no one of these supersymmetric partners has been found, the symmetry must be broken to allow the superpartners to have a much higher mass, allowing them to be not yet discovered. A new quantum number is introduced, called R-parity, defined as:

$$R = (-1)^{3(B-L)+2S}$$

with B , L and S baryon, lepton and spin operators respectively. For ordinary

particles it results $R = 1$, while superpartners correspond to $R = -1$. If R-parity is broken, it means that there are no selection rules to prevent the decay of the supersymmetric particles in the spectrum with masses of order a few GeV or heavier. The scale of R-parity violation regulates the strength of baryon and lepton number violation processes, which have not been observed in nature so far and severe constraints on R-parity violation arise. If this R number is conserved, then a lightest supersymmetric particle (LSP) will have to be stable.

The smallest SUSY extension to the SM is called Minimal Supersymmetric Standard Model (MSSM). In [55] is presented an introduction to the SUSY model with motivation, lagrangian construction, supersymmetric particles, MSSM and some his extensions.

Assuming supersymmetric models with the LSP being the lightest mass eigenstate of a general superposition of neutral spin 1/2 fermions, namely the photino (the superpartner of the photon), the zino (the superpartner of the Z_0 boson) and the higgsino (the superpartner of the neutral Higgs boson), the so-called neutralino turns out to be an ideal DM candidate. The cosmic abundance of the neutralino would be determined by the freeze-out from thermal equilibrium (see eq.(1.4)) with their annihilation and scattering cross sections, as well as masses depending on specific parameters of the assumed supersymmetric model.

Despite the strong theoretical motivation for supersymmetry, no convincing experimental evidence for the existence of supersymmetric particles has been found until today. The search for supersymmetric particles, with masses proclaimed to be around the weak scale, is one of the prime goals of today and next generation accelerators. In particular the Large Hadron Collider results put severe limits to the SUSY parameters and ruled out a lot of models [56]. Until positive results from the accelerator side, the cosmological need for a suitable CDM candidate is the strongest empirical hint to supersymmetry.

Beyond the discussed neutralino, there are other DM candidate particles, which currently seem almost impossible to detect and which are beyond the scope of this work. For instance, the gravitino, the spin 3/2 superpartner of the graviton, the mediator particle of gravity states from the “hidden sector” and thought responsible for supersymmetry breaking, can be a stable particle with masses in the TeV range. This would be the case, if the gravitino is the LSP of R-parity conserving supersymmetric models. Another candidate is the axino, the spin 1/2 superpartner of the axion (discussed in the previous section).

Chapter 2

Dark Matter detection

2.1 Introduction

As seen in the previous chapter, there are many compelling proofs of the DM existence, but, despite this, practically nothing is known about it. Hence it is comprehensible the huge effort to determine its characteristics. Many experiments have been build or designed to detect WIMPs, the today most favorite DM candidate. Beside the detection (direct or indirect, see below), there is also the possibility to directly produce these particles with accelerators, of course with a very small cross-section. Only combining the informations provided by many different experimental approaches, the mystery of Dark Matter particle nature could be solved.

In the next sections, a brief description of the possible experimental strategies for DM search will be given, mostly focusing on the direct detection approach. In particular, the calculation of the expected WIMP rate in a detector and its annual modulation will be discussed. At the end of the chapter a short overview of the actual direct DM search situation will be done.

2.2 Detection strategies

The DM search can be faced with three different methods: accelerator production, direct and indirect detection. Each one can bring a different piece to the global mosaic. If the detection approach is of primary importance to proof the DM existence, nevertheless it is not capable to identify its nature. On the contrary the accelerator production is the only strategy that allow to identify a long lived weakly interacting particle, but is not be able to test its cosmological stability or abundance.

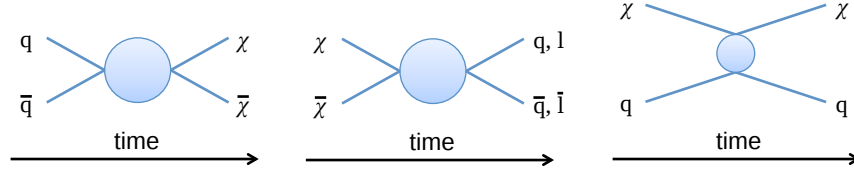


Figure 2.1: WIMPs production/detection strategy schemas. Left: accelerator production. Middle: indirect detection. Right: direct detection.

Accelerators (production schema in fig.2.1 left) are designed to characterize particle phenomena at the electroweak symmetry breaking scale (the TeV scale). With such mass values, these particles have QCD color and therefore will be pair-produced at the LHC with a cross section in the tens of picobarns [57]. Hence, if DM is related to this new physics, it is possible that accelerators, like LHC second phase and the future International Linear Accelerator (ILC), may produce WIMPs.

Given their very small cross section, WIMPs are expected to escape detector without leaving energy in it. Consequently their fundamental signature is missing energy and momentum from a particle collision. The signature of WIMPs at the LHC would be events with many hadronic jets and an imbalance of measured momentum [58]. Direct collider constraints upon the lightest neutralino or other WIMP candidates tend to be extremely model dependent.

Indirect detection (fig.2.1 middle) is based on the search of the WIMPs annihilation products. This can happen, for example, if the WIMP is the neutralino, which is a Majorana particle and therefore it is the antiparticle of itself. The annihilation of two neutralinos can occur in the galactic halo or inside astrophysical objects like the Sun or the Earth, where it should be enhanced because of the accumulation of WIMPs due to gravity.

When WIMPs annihilate, they can produce quarks, leptons, gauge bosons, Higgs bosons and gluons. One of the most favorable experimental channels is the search for positrons. The origin of positrons comes when heavier particles either decay and/or hadronize. WIMP annihilation is then expected to produce an equal mixture of electrons and positrons, but this raises the generally low positron-electron ratio from more trivial background processes. Therefore WIMP annihilation should appear as a broad excess of high energy positrons, inconsistent with the declining power laws expected from background processes. In the last years, multiple experiment results have been interpreted as possible products of WIMPs. The PAMELA experiment, which began its satellite mission in June of 2006, reported an anomalous rise in the cosmic ray positron flux above $20 \div 30$ GeV [59]. This rise can be accounted only considering also the positron production due to the DM [60]. The PAMELA positron to positron-plus-electron ratio as a function of the energy in comparison with other experiment results is shown in fig.2.2 [61, 62, 63, 64, 65, 66, 67, 68]. The PAMELA, AMS-02 and Aesop data under 5 GeV are systematically lower than the other data, which have been collected during the 90's. This behavior can be attributed

to a consequence of charge-sign solar modulation effects of the previous solar cycle.

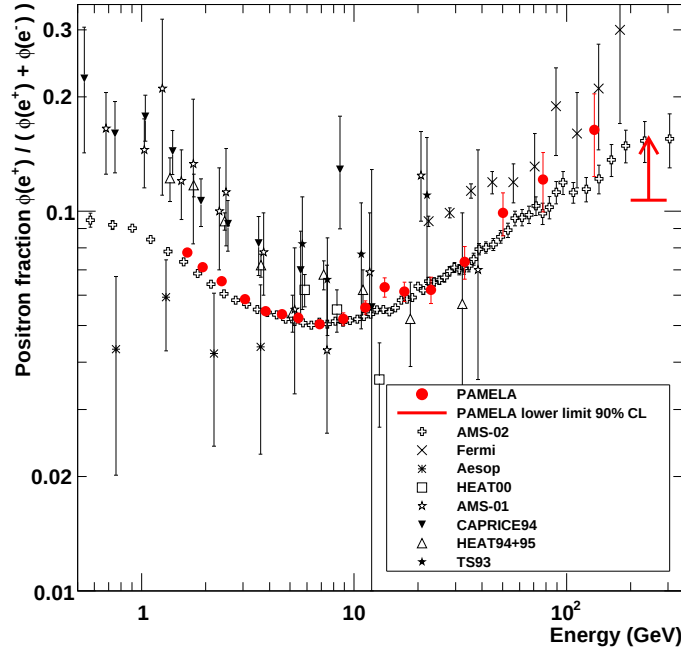


Figure 2.2: PAMELA and other experiments measurement of the positron fraction: TS93 [61], HEAT94+95 [62], CAPRICE94 [63], AMS-01 [64], HEAT00 [65], Aesop [66], Fermi [67], AMS-02 [68]. The PAMELA, Fermi, AMS-01 and AMS-02 results are from space-borne experiments. The behavior of PAMELA, Aesop and AMS-02 below 5 GeV is due to a different solar cycle with respect the other experiments (which belong to the previous one). Figure from [59].

Additional informations can be obtained by muon neutrinos, that can be produced by annihilation of neutralinos trapped inside the Sun or the Earth. Neutrinos, like gamma rays, keep their original direction and for this reason they are now one of the most promising hopes for indirect detection methods with present and future neutrino telescopes. For example, the SuperKamiokande neutrino detector [69], the IceCube experiment [70] or the ANTARES neutrino telescope [71] can set limits on the rate of WIMP annihilations in the Sun.

Direct searches for WIMPs (2.1 right) are carried on in low-background underground experiments, where the direct signal of a WIMP interaction with the target nucleus is detected. This signal is given by the nucleus recoiling after the WIMP elastic scattering. As it will be explained, the energy spectrum of the recoils increases roughly exponentially towards low energies and extends up to

several tens of keV. Its shape depends on the WIMP mass, the mass of the target nucleus and the WIMP velocity distribution.

2.3 WIMP rate in a detector

The differential rate per unit mass of elastic nuclear recoils is expected to be featureless and smoothly decreasing, with the typical form [72]:

$$\frac{dR}{dE_R} = \frac{R_0}{E_0 r} e^{-E_R/E_0 r} \quad (2.1)$$

where E_R is the recoil energy, R_0 is the total event rate, E_0 is the most probable incident kinetic energy of WIMP of mass M_χ and $r = 4M_\chi M_A / (M_\chi + M_A)^2$ is a kinematic factor for a target nucleus of mass M_A . This equation represents the simplest case of a detector stationary in the Galaxy. In practice eq.(2.1) is considerably more complicated due to several corrections:

- The total rate depends on the wimp-nucleon coupling. Results will be different for spin-dependent and spin-independent interactions.
- The target consists of more than one element.
- The detector is not stationary in the Galaxy. It is on the Earth, orbiting around the Sun, moving through the Galaxy with a velocity $v_E \simeq 230$ km/s.
- A nuclear form factor correction must be also taken into account, owing to the nucleus finite size and depending mostly on nuclear radius and recoil energy.
- In most of the detectors, only a fraction of the whole recoil energy is detected. True recoil energy differs from the observed one by a quenching factor $f_n \leq 1$ depending on target material and detection strategy.

2.3.1 Particle density and velocity distribution

Differential WIMP density is given by

$$dn = \frac{n_0}{k} f(\vec{v}, \vec{v}_E) d^3v \quad (2.2)$$

where

$$k = \int_0^{2\pi} d\phi \int_{-1}^{+1} d(\cos \theta) \int_0^{v_{esc}} f(\vec{v}, \vec{v}_E) v^2 dv$$

is the normalization constant. Here $n_0 = \rho_\chi / M_\chi$ is the mean WIMP number density for DM density ρ_χ (standard value is $0.3 \text{ GeVc}^{-2} \text{cm}^{-3}$), $\vec{v}$ is the WIMP velocity relative to the Earth, $\vec{v}_E$ represents Earth velocity relative to

the Galaxy, v_{esc} is the local Galactic escape velocity (typical value is 600 km/s) and dn is the particle density of DM with relative velocities within d^3v about $\vec{v}$. Assuming a Maxwellian DM velocity distribution with average $v_0 = 220$ km/s

$$f(\vec{v}, \vec{v}_E) = e^{-|\vec{v} + \vec{v}_E|^2/v_0^2},$$

we obtain, using $v_E \simeq v_0$,

$$k = k_1 = k_0 \left[\operatorname{erf} \left(\frac{v_{esc}}{v_0} \right) - \frac{2}{\pi^{1/2}} \frac{v_{esc}}{v_0} e^{-v_{esc}^2/v_0^2} \right],$$

where $k_0 = (\pi v_0^2)^{3/2}$ is the normalization in case of $v_{esc} = \infty$.

2.3.2 Differential rate

The event rate per unit mass on a target of atomic number A is

$$dR = \frac{N_0}{A} \sigma_A v dn$$

where N_0 is the Avogadro number ($6.02 \times 10^{26} \text{ kg}^{-1}$) and σ_A is the “zero momentum transfer” cross-section per nucleus. In the case of spin-independent interaction, this cross-section can be easily obtained as

$$\sigma_A = \sigma_0 \frac{\mu_A^2}{\mu_n^2} A^2 \quad (2.3)$$

where σ_0 is the WIMP-nucleon cross-section, $\mu_A = M_A M_\chi / (M_A + M_\chi)$ is the reduced mass of the system “WIMP-nucleus” and μ_n is the reduced mass of the system “WIMP-nucleon”. Then:

$$R = \frac{N_0}{A} \sigma_A \int v dn = \frac{N_0}{A} \sigma_A n_0 \langle v \rangle. \quad (2.4)$$

R_0 is defined as the event rate per unit mass for $v_E = 0$ and $v_{esc} = \infty$:

$$R_0 = \frac{2}{\pi^{1/2}} \frac{N_0}{A} \frac{\rho_\chi}{M_\chi} \sigma_A v_0. \quad (2.5)$$

Substituting eq.(2.2) and eq.(2.5) in eq.(2.4), we obtain

$$R = R_0 \frac{\pi^{1/2}}{2} \frac{\langle v \rangle}{v_0} = R_0 \frac{k_0}{k} \frac{1}{2\pi v_0^4} \int v f(\vec{v}, \vec{v}_E) d^3v$$

and the differential form

$$dR = R_0 \frac{k_0}{k} \frac{1}{2\pi v_0^4} v f(\vec{v}, \vec{v}_E) d^3v. \quad (2.6)$$

The recoil energy of a nucleus struck by a WIMP of kinetic energy $E = \frac{1}{2} M_\chi v^2$, scattered in centre of mass at angle θ , is

$$E_R = Er(1 - \cos \theta)/2$$

with r defined at the beginning of sec.2.3.

Assuming the scattering isotropic, the recoils are uniformly distributed in E_R over the range $0 \leq E_R \leq Er$. Thus

$$\frac{dR}{dE_R} = \int_{E_{min}}^{E_{max}} \frac{1}{Er} dR(E) = \frac{1}{E_0 r} \int_{v_{min}}^{v_{max}} \frac{v_0^2}{v^2} dR(v),$$

where we define $E_0 = \frac{1}{2} M_\chi v_0^2 = (v_0^2/v^2) E$, while $E_{min} = E_R/r$ is the smallest particle energy that can give a recoil energy of E_R and v_{min} is the DM particle velocity corresponding to E_{min} , *i.e.*

$$v_{min} = \sqrt{\frac{2E_{min}}{M_\chi}} = v_0 \sqrt{\frac{E_R}{E_0 r}}.$$

Substituting into eq.(2.6) it results

$$\frac{dR}{dE_R} = \frac{R_0}{E_0 r} \frac{k_0}{k} \frac{1}{2\pi v_0^2} \int_{v_{min}}^{v_{max}} \frac{1}{v} f(\vec{v}, \vec{v}_E) d^3v$$

that, with non-zero v_E and finite $v_{max} = v_{esc}$, gives

$$\frac{dR}{dE_R} = \frac{k_0}{k_1} \frac{R_0}{E_0 r} \left\{ \frac{\pi^{1/2}}{4} \frac{v_0}{v_E} \left[\operatorname{erf} \left(\frac{v_{min} + v_E}{v_0} \right) - \operatorname{erf} \left(\frac{v_{min} - v_E}{v_0} \right) \right] - e^{-v_{esc}^2/v_0^2} \right\}. \quad (2.7)$$

2.3.3 Scalar and axial-vector interactions

In the above equations only the spin independent scattering was considered. Nevertheless, the interactions between nuclei and WIMP can be of two types, depending on the WIMP-quark coupling:

- scalar or spin-independent interaction (SI): happens through the exchange of a squark or a Higgs and can be very important, especially for heavier nuclei;
- axial-vector or spin-dependent interaction (SD): happens through the exchange of a squark or a Z boson.

The theoretical calculations leading to the WIMP-nucleus cross-section from the WIMP-quark coupling will not be discussed here. The total WIMP-nucleus elastic cross section for an element with mass number A can be written as:

$$\sigma_A = \sigma_{A,SI} + \sigma_{A,SD}$$

While the spin-independent cross section is proportional to $\mu_A^2 A^2$ (as can be seen in eq.(2.3)), the spin-dependent cross section is proportional to $\mu^2 I_s$ [73]. The factor I_s has the form

$$I_s = (a_p \langle S_p \rangle + a_n \langle S_n \rangle)^2 J(J+1)$$

where a_p and a_n are the effective WIMP-nucleon couplings, $\langle S_p \rangle$ and $\langle S_n \rangle$ are the expectation values of the proton and neutron spins within the nucleus and J is the total nuclear spin. Only nuclei with non-zero J can have SD interactions.

2.3.4 Nuclear form factor correction

So far, the dependence on the momentum transfer ($q = \sqrt{2M_A E_R}$) was neglected. When the wavelength $\hbar/q$ is no longer large compared to the nuclear radius, the cross-section decreases with increasing q . It is useful to introduce a “nuclear form factor” F , function of the dimensionless quantity qr_n (using natural units, in which $\hbar = 1$), where r_n is the effective nuclear radius. Cross-sections then behave as

$$\sigma(qr_n) = \sigma_0 F^2(qr_n)$$

considering the two different cases of SI and SD interactions. Several multi-parameter fits to charge density have been proposed to calculate SI $F(qr_n)$. Among them, the distribution proposed by Helm [74] has the advantage of yielding an analytic form factor expression:

$$F(qr_n) = 3 \frac{j_1(qr_n)}{qr_n} e^{-(qs)^2/2}$$

where $s \simeq 0.9$ fm is a measure of the nuclear thickness and j_1 is the Bessel function:

$$j_1(qr_n) = \frac{\sin(qr_n) - qr_n \cos(qr_n)}{(qr_n)^2}.$$

Nuclear radius can be approximated by equation:

$$r_n^2 = c^2 + \frac{7}{3} \pi^2 a^2 - 5s^2,$$

where $a \simeq 0.52$ fm and $c \simeq (1.23A^{1/3} - 0.60)$ fm. In fig.2.3 are reported the obtained form factors for some typical nuclei.

In the case of SD interactions, a useful approximation is to consider only the contribution coming from the unpaired nucleon (“single particle model”) or from nucleons of the same type as the unpaired nucleon (“odd-group model”). In this case the form factor can be written:

$$F(qr_n) = j_0(qr_n) = \frac{\sin(qr_n)}{qr_n}.$$

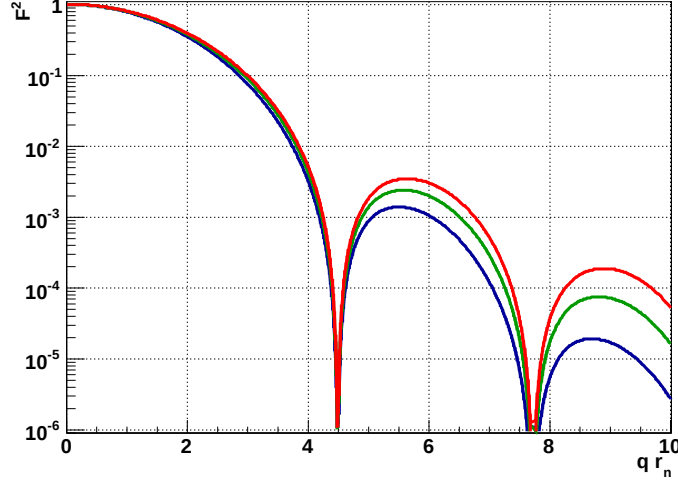


Figure 2.3: SI nuclear form factors for ^{131}Xe (in red), for ^{40}Ar (in blue) and for ^{73}Ge (in green).

More precise calculations have been carried out for a small number of nuclei (for example see [75] and [76]).

2.3.5 Quenching factor

The signal induced by a nuclear recoil of a given energy is usually less than the signal produced by an electron recoil of the same energy. This is due to the different energy percentages going to detectable channels (light or electric charge, for example) and to undetectable ones (for example heat). The ratio f_n between observed energy and true energy is named quenching factor and can be determined by neutron scattering measurements. While spectra could be directly expressed in terms of E_R , it is usually preferred to work with the γ calibrated energies for easier identification of γ background. Consequently E_R in the above formulas should be replaced by the “visible” energy E_v , using $E_R = E_v/f_n$ and, considering possible variations of f_n with E_R ,

$$\frac{dR}{dE_R} = f_n \left(1 + \frac{E_R}{f_n} \frac{df_n}{dE_R} \right) \frac{dR}{dE_v}.$$

2.3.6 Combining results

All the equations above are strongly dependent on mass number A . Since detectors are often composed by several different materials, one has to consider the different contribution of each of them. The total differential recoil rate per kg of target mass can be obtained by

Isotope	A	Natural abundance in Te	TeO ₂ mass fraction (x_A)
¹²⁰ Te	120	0.0009	0.0008
¹²² Te	122	0.0255	0.0204
¹²³ Te	123	0.0089	0.0071
¹²⁴ Te	124	0.0474	0.0379
¹²⁵ Te	125	0.0707	0.0565
¹²⁶ Te	126	0.1884	0.1506
¹²⁸ Te	128	0.3174	0.2538
¹³⁰ Te	130	0.3408	0.2725
¹⁶ O	16		0.2004

Table 2.1: TeO₂ bolometers compositions. Data from [78].

$$\left. \frac{dR}{dE_R} \right|_{total} = \sum_A x_A F_A^2 \left. \frac{dR}{dE_R} \right|_A$$

where F_A^2 is the nuclear form factor for a target nucleus with mass number A, $dR/dE_R|_A$ its differential rate calculated in eq.(2.7) and x_A its fraction of the total target mass.

For example, TeO₂ bolometers (that will be introduced in the next chapter) are composed by several different Te isotopes and ¹⁶O atoms (see tab.2.1), with $f_n \simeq 1$ since in bolometers the whole energy is converted into phonons and fully detected [77]. Moreover, SD interactions in TeO₂ are negligible because it is composed almost exclusively by spin-0 nuclei and, even for the small non-zero spin isotopes, scalar cross-sections are favored by the high mass number. The obtained TeO₂ spectral function is shown in fig.2.4.

2.4 The annual modulation

It is important to stress out that only some experiments are able to distinguish nuclear recoils from other background events, exploiting the different interaction features of the various particles in the detector. Without this capability, direct DM searches become more complex.

In fact, the energy spectrum of WIMP-induced nuclear recoils, which can be calculated using the above formulas, is exponentially decreasing with the recoil energy in the typical range 1 ÷ 100 keV and, unfortunately, its shape is smooth and featureless. The absence of any feature in the spectrum and the low energy region where it is confined makes it practically impossible to distinguish this signal from the low energy background of the detector, which comes partially from intrinsic sources (radioactive contaminations inside the detector itself or in the nearby material) and partially from external sources, like cosmic rays and neutrons entering the detector area. It is clear now that it is impossible to detect a “positive” WIMP signal just by looking at the shape of the experimental spectrum. However, the absence of a positive signal does not mean no result at

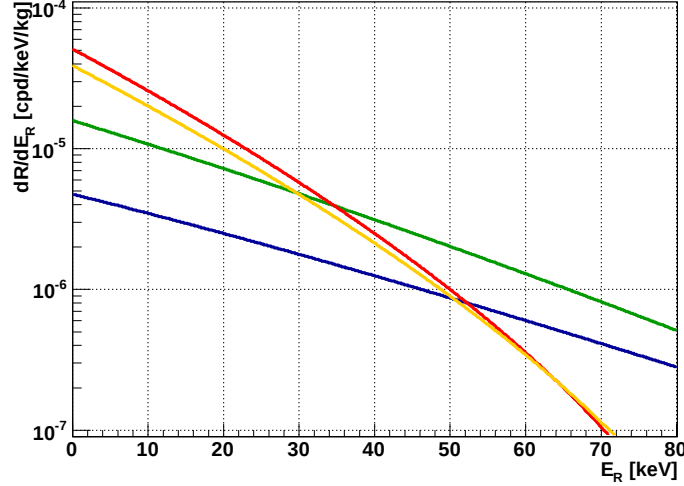


Figure 2.4: Differential rate of WIMP SI elastic scattering on TeO_2 (yellow), on ^{131}Xe (red), on ^{40}Ar (blue) and on ^{73}Ge (green), for $M_\chi = 100 \text{ GeV}$ and $\sigma_0 = 10^{-45} \text{ cm}^2$.

all: every experiment, providing an observation of nuclear recoils at low energy, can set limits on the WIMP presence in our Galaxy, excluding those WIMPs that would produce a nuclear recoil event rate higher than observed. Moreover, a reduction of the background, obtained for example working in an underground site or using background suppression or discrimination methods, increases the sensitivity of the detector and allows the experiment to set more and more stringent limits to the WIMP parameters.

Saying that the WIMP induced nuclear recoil spectrum has no distinctive features is true for the shape of the spectrum but not for the WIMP signal in general. The recoil spectrum produced by WIMP-nucleus scattering in a target detector is expected to show the so-called annual modulation effect [79]. Since Earth rotates around the Sun and the Sun itself moves into the galactic reference frame (see fig.2.5 left), we can express the Earth speed with respect the Galaxy (v_E) as the sum of the two motions:

$$v_E = v_\odot + \langle v_{rot} \rangle \cos \gamma \cos(\omega(t - t_0))$$

where $v_\odot$ is the Sun speed in the galaxy, $\langle v_{rot} \rangle$ is the average Earth speed in its motion around the Sun and γ is the angle between the Earth rotation plane and the galactic plane. The period and phase of the cosinus function are known to be $\omega = 2\pi/T$ ($T = 1 \text{ y}$) and $t_0 = 2^{nd}$ June. It is customary to express the Earth velocity in units of the parameter v_0 , defined above as the parameter of the Maxwellian WIMP speeds distribution function. The adimensional quantity $\eta = v_E/v_0$ shows the following time dependence:

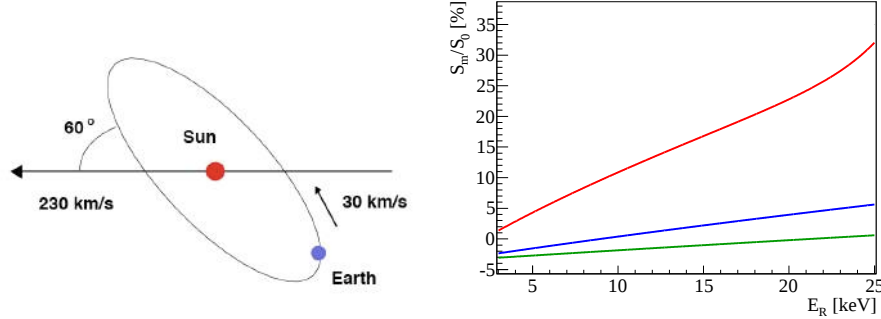


Figure 2.5: Left: The combined motion of the Earth around the Sun (average velocity $\langle v_{rot} \rangle = 30$ km/s) and of the Sun itself with respect to the galaxy ($v_{\odot} = 232$ km/s) is responsible for the annual modulation effect. Right: Predicted ratio of the modulated to the constant WIMP signal in TeO_2 for $M_{\chi} = 20$ GeV in red, $M_{\chi} = 50$ GeV in blue and $M_{\chi} = 100$ GeV in green.

$$\eta(t) = \eta_0 + \Delta\eta \cos(\omega(t - t_0))$$

where the amplitude of the annual modulated component ($\Delta\eta \simeq 0.07$) is small compared to the average value $\eta_0 \simeq 1.05$. In this framework, the expected WIMP signal in the Earth reference system can be written (first order Taylor approximation):

$$S = S_0 + S_m \cos(\omega(t - t_0))$$

where $S_0 = S(\eta_0)$ is the time independent signal and $S_m = \left. \frac{\partial S}{\partial \eta} \right|_{\eta_0} \Delta\eta$ is the amplitude of the modulated signal. As we can see from the expressions of S_0 and S_m and from fig.2.5 right, the amplitude of the annual modulation is only a few percent of the time independent signal, strongly dependent on M_{χ} and E_R . Moreover, its contribution to the total signal S can be not only positive but also negative or zero. To point out the presence of such fluctuation, superimposed on a constant count rate of WIMP interactions but also background from other sources, is not an easy task. What is needed is a large mass detector, with a background well stable over time and high exposure time.

Despite the difficulties related with its detection, the annual modulation effect remains the main signature of a possible DM signal, a positive indication that, if observed, would allow to constrain the WIMP parameters space with an allowed region instead of several exclusion plots. It is important to point out that two different analysis can be performed in this case: a model independent analysis, in which only the presence of the modulation is looked for in the data and a model dependent analysis, where, assuming a complete model framework, it is possible to allow (or to exclude) a region in the space of the parameters M_{χ} and σ . Therefore, if a modulation signature is discovered in the experimental

data, it is possible to extract informations on the WIMP relevant quantities only in the framework of a given model (for example: SI WIMP-nucleon interactions, non rotating halo, Maxwellian distribution of WIMP velocity, Galactic escape velocity and so on).

2.5 WIMP direct detection techniques

A variety of techniques are presently in use for WIMP searches. Due to the numerous ways to achieve sensitivities to the WIMP properties (high A , high target mass, low threshold, low background, background rejection and background subtraction techniques, etc.), only a few, among the most successful and most promising ones, are discussed in this section. One of the main difficulties of any such technique is the low signal rate to be expected from supersymmetric model calculations. The typical counting rates are much lower than the usual radioactive backgrounds. Therefore, common to all WIMP searches, is the goal to reduce the natural radioactive contamination by using extremely pure substances and to actively reject background events by special techniques.

Experimentally, there are several ways of particular importance to measure the event rate of WIMP-nucleus collisions discussed previously. First, one may search for scintillation light created by the energy deposit of the WIMP in the target detector, as NaI or Xe detectors. Hereby, the recoiling particle, directly or indirectly, excites electrons to energy levels above their ground states, from which they may decay by emission of ultraviolet or visible photons. Due to the reasonably low backgrounds, by using ultrapure materials, and large masses achievable, scintillators are naturally used for annual modulation searches. This has been successfully done by DAMA/NaI and DAMA/LIBRA experiments at Laboratori Nazionali del Gran Sasso (Italy), which claims to have found an annual modulation on data taken over several annual cycles [80]. Fitting data with the function $A \cos \omega(t - t_0)$, two cases are taken into consideration. The first with fixed parameters, $T = \frac{2\pi}{\omega} = 1 \text{ y}$ (period) and $t_0 = 152.5 \text{ d}$ (maximum position, June 2nd), that gives $A = (0.0110 \pm 0.0012) \text{ counts/day/kg/keV}$, corresponding to 9.2σ C.L. The second approach leaves free all the parameters in the fitting procedure, resulting in: $A = (0.0112 \pm 0.0012) \text{ counts/day/kg/keV}$ (9.3σ C.L.), $T = (0.998 \pm 0.002) \text{ y}$ and $t_0 = (144 \pm 7) \text{ d}$. With the measured effect, the collaboration obtains a model independent evidence for the presence of a DM particle component in the galactic halo (see fig.2.6).

However, the deduced allowed region for the WIMP mass and the WIMP-nucleon cross section is excluded by many other experiments (see fig.2.7). Without regard to the exception of annual modulation, the described detection technology offers little or no direct background rejection capability. An important background rejection technique, possible with many detectors, is nuclear recoil discrimination. In NaI scintillators, this can be achieved by pulse shape analysis, since nuclear recoils produce scintillation pulses that decay more quickly than those produced by electron recoils.

Liquid noble gas detectors with scintillation readout have shown competi-

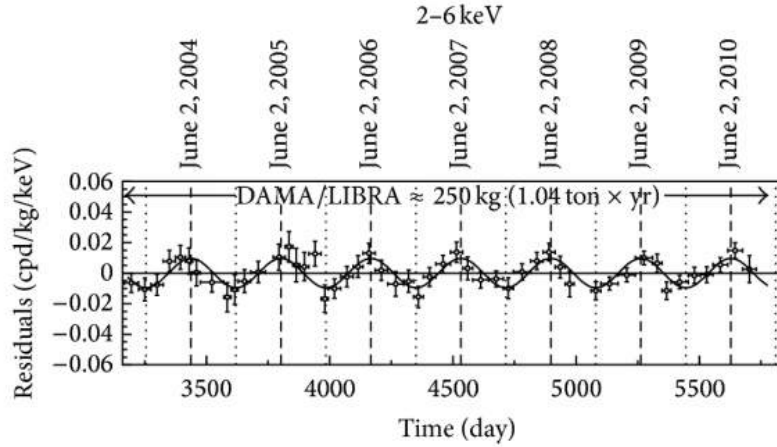
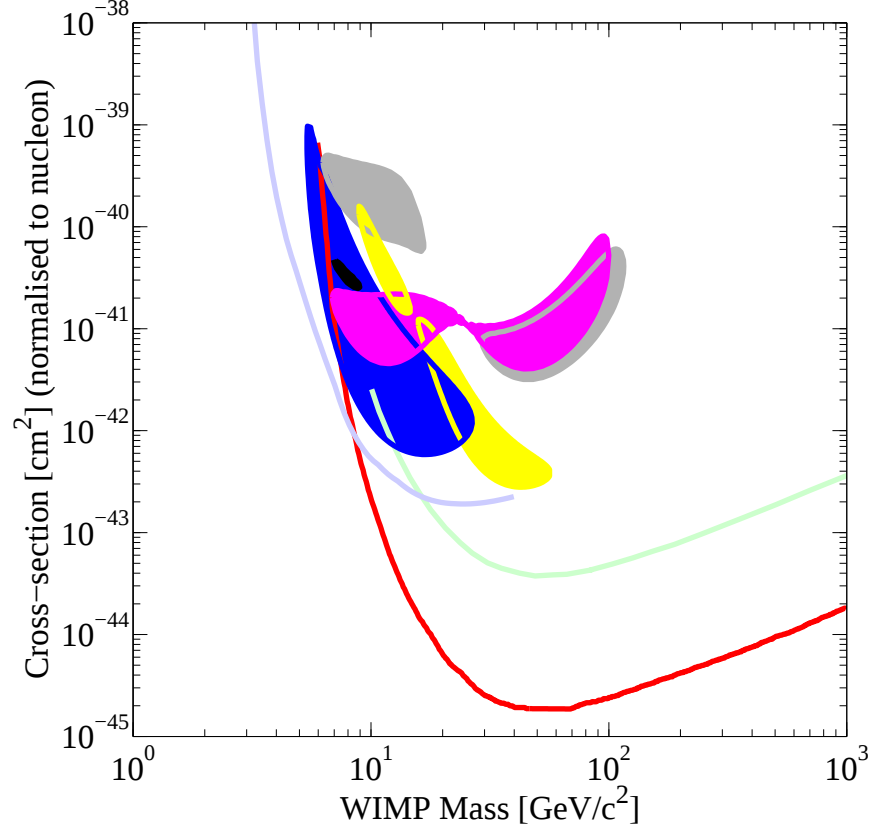


Figure 2.6: Experimental residual rate of DAMA of the single hit scintillation events measured by DAMA/LIBRA-phase1 in the $(2 \div 6)$ keV energy interval as a function of the time. Vertical bars are the experimental point errors, while the orizzontal bars the time bin width. The superimposed curve is the expected signal modulation: $A \cos \omega(t - t_0)$, with period $T = \frac{2\pi}{\omega} = 1 \text{ y}$, maximum at $t_0 = 152.5 \text{ d}$ (June 2nd) and amplitude given by central value resulting from the best fit to the data. The dotted and the dashed vertical lines represents the position of minimum and maximum of the expected DM signal modulation, respectively. Depending on the fitting procedure adopted, it results in: $A = (0.0112 \pm 0.0012) \text{ counts/day/kg/keV}$ with A , T and t_0 free to vary, or in $A = (0.0110 \pm 0.0012) \text{ counts/day/kg/keV}$ with fixed T and t_0 . Figure from [80].



DATA listed top to bottom on plot

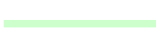
	CoGeNT, 2013, WIMP region of interest, SI
	CRESST II (2011), 730kg-d, 2-sig. , SI pt. 2
	DAMA/LIBRA, 2008, with ion channeling, 3sigma, SI
	DAMA/LIBRA, 2008, no ion channeling, 3sigma, SI
	CDMSII-Si (Silicon), c58 95% CL , SI (2013)
	CRESST II (2011), 730kg-d, 2-sig. allowed region, SI pt. 1
	SuperCDMS Soudan LT, 90% C.L.
	ZEPLIN III, 2011, second science run, 1344kg-days, SI
	XENON100, 2012, 225 live days (7650 kg-days), SI

Figure 2.7: Current limits from various direct DM search experiments in the WIMP mass - WIMP-nucleon cross section (normalized to nucleon) plane. Figure generated using [81].

tive WIMP sensitivities. Most notably has been liquid xenon (LXe), started by the DAMA/LXe experiment [82], but also liquid neon and liquid argon in the DEAP/CLEAN experiments [83]. Liquid argon is also used in the DarkSide collaboration [84]. Furthermore, argon is also used for the ArDM experiment [85], one ton two-phase liquid argon detector, presently under commissioning underground at Laboratorio Subterráneo de Canfranc. LXe as a target for WIMP detection, on the other hand, has particularly good intrinsic properties, *i.e.* high mass, high scintillation and ionization efficiency and high radiopurity. However, the recoil discrimination achievable is of greater importance. This is realized firstly, as in NaI scintillators, by pulse shape analysis of the scintillation light, which is the basis of single-phase LXe experiments such as XMASS [86] in Japan and UK-based ZEPLIN-I [87]. More powerful discrimination in LXe can be achieved by recording also the ionization produced by the WIMP-interaction. The recoiling nucleus travels through the target material before stopping, ionizing atoms as it passes. The lower velocities of nuclear recoils though, induce less ionization relative to the ionization induced by electromagnetic interactions with electrons of the shell by β and γ radiation. This helps to significantly lower the background rate for DM searches. In liquid noble gas detectors this yields to a different ionization/scintillation ratio for nuclear and electron recoils, respectively. This detection principle is implemented by the ZEPLIN-II/III [87, 88, 89], the XENON 10/100/1T [90, 91, 92] and the LUX [93] experiments. To obtain stable operation conditions the current experiments use two-phase LXe. Hereby, the charge produced by the recoil first drifts out of the liquid into a gaseous phase, where a proportional scintillation signal (electroluminescence) can be observed. A future experiment that will use the LXe technique is LZ, born from the merging of LUX and ZEPLIN experiences [94].

Another way to detect WIMP-nucleus collisions in a target detector is to search for the ionization signal in a semiconductor, notably in high-purity germanium detectors. These detectors were initially used to look for the Neutrinoless Double Beta Decay of an isotope in the detector itself (see sec.3.3.1). The main problem of those detectors is the large background rate from natural radioactivity. However, very low limits have been achieved by means of careful material selection and detector shielding (GERDA [95] as example). Among the germanium based experiments, CoGeNT claimed an annual modulation signal few years ago [96]. Also the MAJORANA experiment [97] will be made of germanium detectors, primarily to search for Neutrinoless Double Beta Decay.

A further possibility to search for the energy deposition by a WIMP-nucleus scattering is the cryogenic or bolometric approach. Whereby one may cool the target to very low temperatures of around 10 mK, so that a 10 keV energy deposit causes a measurable proportional increase in the detector temperature (see next chapter for details). This heating can be measured *e.g.* by a superconducting thermometer attached to the target which is shifted toward the normal conducting phase by the temperature increase. The initial prospect of detectors of this type was to obtain very low recoil energy thresholds combined with a very high energy resolution. However, it was soon demonstrated that a simultaneous measurement of the ionization signal, together with the heat or phonon

signal, also provides a good discrimination against electron recoils. In fact, a recoiling nucleus produces proportionally less ionization than an electron recoil of the same energy. Experiments using, or that used, the hybrid technique of simultaneous ionization and heat collection are the EDELWEISS experiment [98], as well as the CDMS II experiment, that claimed a positive results [99]. This claim is in contrast with the recently released results of its upgrade, the SuperCDMS [100].

As an alternative, the CRESST collaboration has developed CaWO_4 cryogenic phonon detectors and pursued the use of scintillation for the second signal channel, next to the heat signal. In particular, instead of using photomultipliers to obtain the scintillation signal, a second phonon-mediated detector with a light absorber is placed adjacent to the primary detector. Also CRESST claimed a DM signal detection [101].

Besides the well established techniques discussed in this section, further approaches to detect DM directly are investigated. One promising technique uses superheated droplets detectors or “bubble detectors”. The goal of these detectors is to detect single bubbles induced by nuclear recoils in heavy liquid bubble chambers. In this implementation of the method, the metastable state of the target liquid is preserved by dispersing it into a viscous/inmiscible gel, effectively resulting in a collection of mini-bubble chambers. The great advantage of this technique, besides the low costs, the room temperature operation and the well known detector technology is the nuclear recoil discrimination power. The energy deposition by an electron recoil is too distributed to cause a bubble to boil, contrary to nuclear recoils. Among the experiments exploiting this technique, there are PICASSO [102] and COUPP [103].

Finally, a powerful, though technologically challenging possibility to proof that a signal is of galactic origin is to correlate events with the Earth’s motion through the galactic WIMP halo. So, the goal is to measure the direction of the recoiling particle and to make use of the diurnal modulation of the signal due to directionality of the “WIMP wind”. This is the motivation behind the DMTPC experiment [104].

Chapter 3

CUORE-0 and the bolometric technique

3.1 Introduction

Among the possible experimental techniques for direct DM detection, the bolometric one is promising. A *bolometer* is a crystal operated as a calorimeter that works at cryogenic temperature (~ 10 mK), in which almost all the energy of an interaction is converted into phonons. CUORE-0 is the largest bolometric experiment ever build and is taking data in the underground Laboratori Nazionali del Gran Sasso. It is originally intended for $0\nu\beta\beta$ decay search of ^{130}Te , but it has been demonstrated that also a DM study can be undertaken with this detector [105].

In this chapter the bolometric technique will be described and subsequently will be given a CUORE-0 presentation and summary.

3.2 Bolometers

Generally the energy released in a detector is lost in various channels, different from the one selected for the particle detection. Differently, in a bolometer this does not happen, because almost all the deposited energy is converted into thermal phonons that rise its temperature. Thus it is possible to measure this temperature increase by means of a thermometer. Given this, a bolometer can be described as composed by two components: an *absorber* and a *sensor*. The absorber is a crystal in which an energy release raises the temperature, while the sensor is the thermometer that measures the variation. Then the accumulated heat is dissipated by means of a coupling to a thermal bath (see fig.3.1).

Given their working principle, bolometers are intrinsically slow detectors (tens of ms), suitable only for low rate experiments.

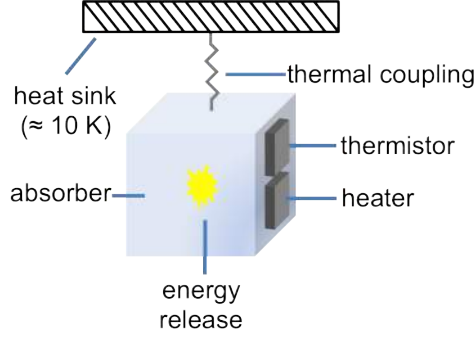


Figura 3.1: Bolometer schema. An interaction with a particle releases energy in the crystal (the absorber), raising its temperature. This temperature variation is measured by means of a thermometer (the thermistor) and then the accumulated heat is dissipated via a coupling to a thermal bath. The heater is an electronic component mainly used for two reasons: find the working point of the bolometer (see sec.3.2.3) and to correct pulse amplitude variation due to temperature oscillation (see sec.5.2).

3.2.1 The absorber

The absorber can be sketched as a capacitance C connected to an heat sink via a conductance G . If C is independent from the temperature T , an energy release E cause a temperature variation ΔT given by:

$$\Delta T = \frac{E}{C}. \quad (3.1)$$

The heat flows through the conductance to the thermal bath until an equilibrium is reached:

$$\Delta T(t) = \frac{E}{C} \cdot e^{-t/\tau}$$

with $\tau = C/G$ characteristic time. To have a large and fast signal (temperature variation), the capacitance C must be very small and this is why bolometers work at cryogenic temperatures ($\lesssim 100$ mK). The specific heat at low temperature of a metal is given by two components, one coming from the lattice and the other coming from the conduction electrons:

$$c(T) = c_R(T) + c_e(T).$$

The $c_R(T)$ part arises from the Debye law

$$c_R(T) = \frac{12\pi^5}{5} N_a k_B \left(\frac{T}{\Theta_D} \right)^3 \quad (3.2)$$

where N_a , k_B and Θ_D are the Avogadro number, the Boltzmann constant and the Debye temperature of the material, respectively.

The $c_e(T)$ electronic component is described by

$$c_e(T) = \frac{ZR}{\Theta_D} \pi^2 \frac{T}{\Theta_F} \quad (3.3)$$

with Z conduction electron number, R gas constant and Θ_D Fermi temperature.

Since $c_R \sim T^3$ and $c_e \sim T$ (from (3.2) and (3.3)) it is obvious that it is convenient to choose dielectric materials, where the contribution of the conduction electrons, dominant at low temperatures, is absent.

3.2.1.1 Intrinsic resolution

In a simplified model, where all the phonons thermalize, it is possible to give an estimation of the energy resolution. In this approximation the energy resolution is limited only by fluctuations of the number of phonons exchanged with the thermal bath. This happens because fluctuations in the number of phonons produce casual variations of the energy contained in the absorber. This energy E can be written as

$$E = C(T) \cdot T,$$

that, in terms of phonons, it becomes

$$E = N \cdot \epsilon$$

where N is the phonon number and $\epsilon = k_B T$ is the phonon average energy. Assuming that phonons obey to the Poisson law ($\Delta N = \sqrt{N}$), with few steps it is possible to demonstrate that the energy fluctuation is described by

$$\Delta E = \Delta N \cdot \epsilon = \sqrt{k_B C(T) T^2}. \quad (3.4)$$

In (3.4) should be inserted an adimensional parameter to consider the experimental setup, but with a correct realization of the experiment this factor is close to 1. Making a calculations with numbers from CUORE-0 ($C \approx 10^{-9}$ J/K and $T = 10$ mK) the resulting resolution is much better than the real one: 10 eV in contrast with the measured $1 \div 2$ keV. This because the real resolution is dominated by other factors, like electronic noise, microphonism, mechanical vibration of the detector, baseline temperature variation, etc.

Particles can interact with the absorber in two ways: via scattering with nuclei or via scattering with electrons; in both cases energy is converted into phonons. In the interaction with the nuclei could happen that the crystal lattice traps part of the energy in some defects avoiding its release, worsening the energy resolution. The fraction of total energy lost in this way depends on the particle nature, being negligible for photons and electrons and of the order of 100 keV for α s of some MeV [106].

In the case of electronic channel, the particle creates electron-holes pairs that rapidly propagate through the detector till a quasi-equilibrium state is reached. Once this condition is obtained, phonons are created by means of the interaction

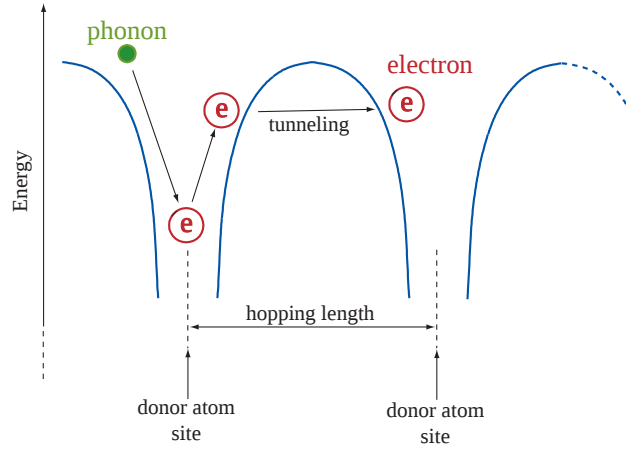


Figura 3.2: Hopping mechanism representation. Electrons can pass from a donor atom site to another; the energy needed for the tunnel effect is provided by phonons.

with the lattice. It is possible that part of this energy escapes from the crystal or remains trapped in stable or meta-stable states, turning into a reduction of the energy resolution given that, also if the energy is released, this would happen in a too long time scale to participate to the signal generation.

3.2.2 Thermal sensor

A semiconductor is a material with a small energy gap between the valence band and the conduction band, but in any case too big for an electron to jump to the conduction level, in particular at low temperature. Typical values are of the order of eV, while at room temperature $k_B T \approx 0.026$ eV. This gap can be reduced using some doping, that, introducing intermediate levels between the two bands, allows conduction also at low temperature. If the dopant concentration is high enough it is possible to obtain a conductor, instead with a slightly lower concentration the material is in the metal-insulator transition region (MIT) where the resistance strongly depends on the temperature [107].

In a doped semiconductor at low temperature (≈ 10 mK) the conduction is dominated by the charge carriers migration from impurity to impurity site. If the impurities are enough, the wave functions of the charge carriers of near impurity atoms are overlapped, so the electrons are no longer localized and are free to jump on different donor sites, without passing through the conduction band. This process, that takes the name of *hopping mechanism* (see fig.3.2), is possible because electrons can pass from an impurity to another via tunnel effect thanks to phonons energy.

At lower temperatures the energy of the phonon responsible of the mechanism is smaller and the charge carriers migrate on far impurity with free energy

levels close to the Fermi energy. In this regime of Variable Range Hopping (VRH) [108] the minority charge carriers is fundamental because it determines the density of the states near the Fermi level. Therefore it is possible to enter transition region varying mutual concentrations of acceptors and donors.

In VRH regime thermal sensor resistivity highly depends on temperature:

$$\rho(T) = \rho_0 \exp \left(\frac{T_0}{T} \right)^\gamma$$

where ρ_0 and T_0 depend on dopant concentration and $\gamma \simeq 1/2$.

In conclusion for examined thermistors, doped with the *Neutron Transmutation Doped*¹ (NTD) method, it is possible to write:

$$R(T) = R_0 \exp \left(\frac{T_0}{T} \right)^\gamma. \quad (3.5)$$

The thermal sensor is a device able to convert a temperature variation in a resistance variation and, by means of a bias current, in an electric signal. The used sensor is a *Semiconductor Thermistor* (ST), which working principle relies on its resistance temperature dependance. These STs are characterized by a sensitivity defined as

$$A = \left| \frac{d \ln R(T)}{d \ln T} \right|$$

and from eq.(3.5) follows that

$$\frac{dR}{R} = A \frac{dT}{T}.$$

Typical values of A for STs are ≈ 10 , with a response of the order of milliseconds.

3.2.3 Signal generation and readout

To read the sensor resistance variation and thus the signal produced by the event in the detector, a polarization circuit for the thermistor is needed as indicated in fig.3.3 left.

The thermistor is polarized through a bias current I_{BIAS} , given by a current generator with a voltage V_{BIAS} . The sensor is positioned between two load resistances $R_L/2$, much larger than $R_{bol}(T)$ of the thermistor. In this way the current across the circuit is practically constant independently of $R_{bol}(T)$. So the voltage at the ends of the thermistor is given by:

$$V_{bol} = I_{bol} \cdot R_{bol}(T)$$

with $I_{bol} = I_{BIAS}$. This voltage can produce a power dissipation on the sensor, described by the law $P = V \cdot I$, that cause a resistance diminution (process

¹This technique consists in thermistors (in the CUORE-0 case germanium parallelepipeds) doping by means of thermal neutrons.

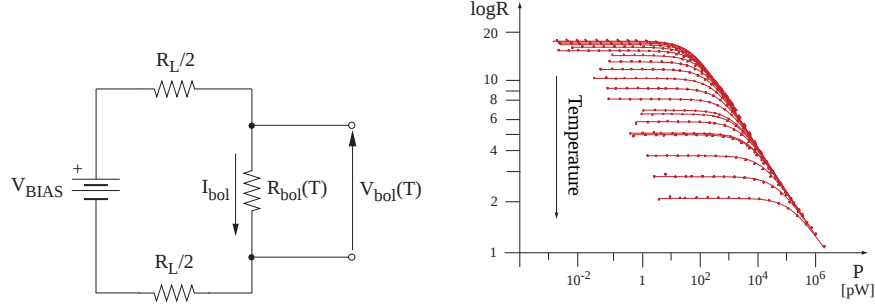


Figure 3.3: Left: thermistor polarization circuit for the readout of the signal generated by an event in the detector. Right: resistance dependence on dissipated power for different temperature values. Curves with lower resistance at $P \simeq 0$ correspond to higher temperatures.

known as *electrotermic feedback*). In this case the thermistor no longer presents an “ohmic” behavior. When the power dissipated on the sensor is equal to the one yields to the thermal bath, an equilibrium condition is obtained. Calling the thermal bath temperature T_0 , in static conditions the sensor temperature results to be

$$T_{bol} = T_0 + \frac{P}{G}$$

where G is the conductance between the bolometer and the thermal bath. In fig.3.3 right the thermistor resistance dependence on the dissipated power is presented.

The non “ohmic” behavior described before lead to a non linearity in the characteristic curve $I - V$, shown in fig.3.4. For little values of current the dissipated power is small, thus the temperature rise is negligible and the curve $I - V$ practically has a liner slope. Increasing the voltage the load curve depart from the linear slope until reaches the inversion point. Over this point a V_{BIAS} augmentation produces a voltage decrease at the ends of the thermistor. The best working point is the one that optimizes the signal-to-noise ratio (SNR), obtained for voltages larger than the one that maximizes the signal amplitude (always shown in fig.3.4). Its search is pursued first looking for the voltage corresponding to the highest signal amplitude, then rising V_{BIAS} until the maximum is reached in the SNR, since noise decreases faster than the signal. One of the functions of the heater (an electronic component of the detector that releases a constant amount of energy in the bolometer) is to allow a fast search of the working point. Indeed, thanks to the constant intensity of its signal, it is not necessary to build the entire spectrum of the detector, but just to measure the pulse height for any V_{BIAS} applied to the thermistor.

When an interaction releases energy in the crystal there is a consequent

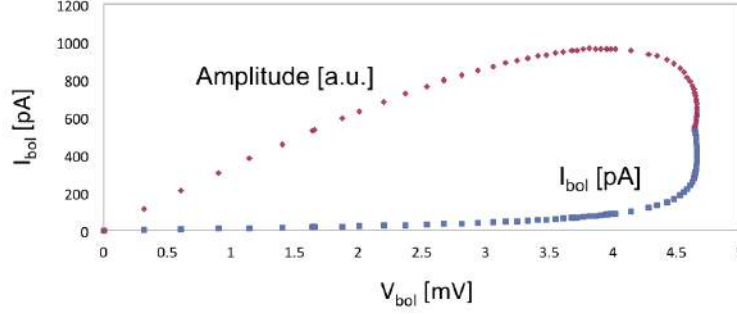


Figura 3.4: Load curve (blue squares) and corresponding signal amplitude (red rhombus) for a bolometer. The load curves shows a non “ohmic” behavior as V_{BIAS} increases: the slope deviates from linearity until reaches the inversion point, above which any additional increase of V_{BIAS} determines a diminution of the voltage V_{bol} at the ends of the thermistor. The best working point is not the one corresponding to the largest signal amplitude, but the one that optimize the SNR (obtained with V_{BIAS} above the value that maximize the signal amplitude).

temperature raise, that results in a thermistor voltage variation. The thermistor voltage is given by

$$V_{bol} = V_{BIAS} \frac{R_{bol}}{R_{bol} + R_L}$$

while the voltage variation due to an energy release E is described by

$$\Delta V = AV_{bol} \frac{\Delta T}{T_{bol}} = A\sqrt{PR_{bol}} \frac{E}{CT_{bol}} \quad (3.6)$$

having used eq.(3.1) and $V_{bol} = PR_{bol}$, where P is the power dissipated on the thermistor. Eq.(3.6) tells that signal amplitude goes to zero trivially for $P \rightarrow 0$ and $P \rightarrow \infty$ because the logarithmic sensitivity and the resistance decrease very rapidly.

In fig.3.5 it is shown the typical pulse produced by an interacting particle in a bolometer. In addition to the amplitude, other two variables are useful to define it: the *rise time* and the *decay time*. The first is the time needed to pass from the 10% to the 90% of the amplitude before the maximum (~ 10 ms), while the latter is the time needed to pass from the 90% to the 30% of the amplitude after the maximum (~ 100 ms).

It is possible to evaluate the signal amplitude for an experiment like CUORE-0, where $C \simeq 10^{-9}$ J/K at 10 mK. An event that releases ≈ 1 MeV of energy in the detector produces a temperature rising of ~ 0.1 mK (see eq.(3.1)) and given that $\Delta V/V = A\Delta T/T$, with $V \sim 1$ mV and $A \approx 10$, it results $\Delta V \sim 100 \mu V$.

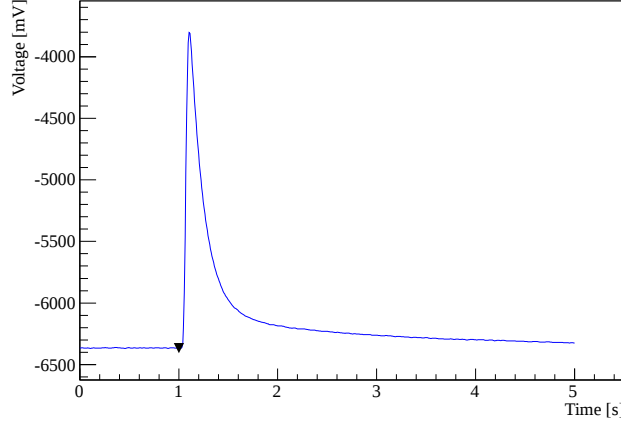


Figura 3.5: Typical pulse produced in a bolometer after the energy release by an interaction in the crystal, in this case a 2615 keV event in a TeO_2 bolometer. The black triangle is the trigger flag and the first second in the acquired window consists of the so-called “pretrigger” points.

3.3 CUORE-0

The CUORE-0 detector is a fundamental step towards the CUORE (Cryogenic Underground Observatory for Rare Events) experiment, which principal aim is to search for the neutrinoless double beta decay of ^{130}Te [109, 110]. The detector will consist of 988 $5 \times 5 \times 5 \text{ cm}^3$ TeO_2 crystals of 750 g each (for a total mass of 741 kg) grouped in 19 towers, all identical to CUORE-0, which has been build to test the tower assembly line. CUORE will be hosted in a dedicated hut in the Hall A of the underground Laboratori Nazionali del Gran Sasso (LNGS) in Italy, under 3650 meters of water equivalent of rock shielding from cosmic rays. Data taking will start in 2015 and will lasts for 5 years.

Firstly the neutrinoless double beta decay will be briefly described and then the CUORE-0 detector and statistics will be presented.

3.3.1 Neutrinoless Double Beta Decay

The double beta decay is a very rare process, where the involved nucleus changes its atomic number by two unity:

$$(A, Z) \longrightarrow (A, Z \pm 2)$$

In particular if two neutrons transform in two protons ($Z \rightarrow Z + 2$) it is a negative double beta ($\beta^-\beta^-$), instead if two protons transform in two neutrons ($Z \rightarrow Z - 2$) it positive double beta ($\beta^+\beta^+$). Being a second order process it has a very small probability to occur and it is possible only when the normal beta

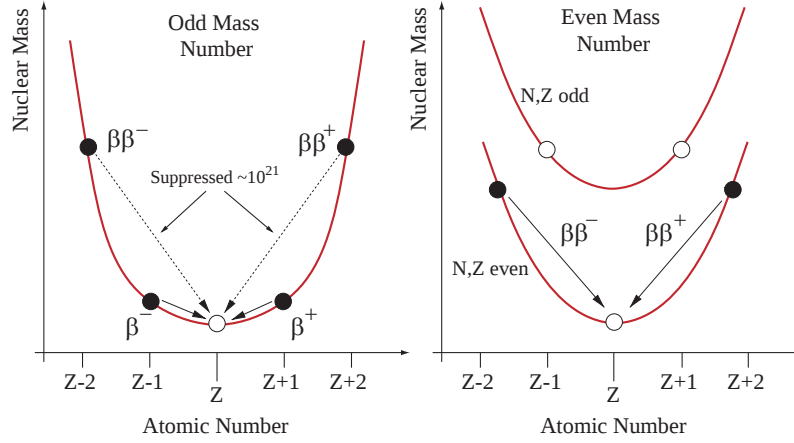


Figure 3.6: Atomic mass as a function of atomic number for odd (left) and even (right) atomic number.

decay is forbidden. Even-even nuclei (even number of protons and neutrons) are favorites with respect odd-odd nuclei (odd number of protons and neutrons), because in the former case is more probable the realization of the condition that the starting nucleus (A, Z) is less bounded than the final one $(A, Z \pm 2)$, but more bounded than the intermediate status $(A, Z \pm 1)$, as shown in fig.3.6.

If two neutrinos are emitted during the decay ($2\nu\beta\beta$, fig.3.7 left), this is a process allowed by the SM and observed for the first time in 1987 for ^{82}Se [111]. Nowadays around thirty atoms that decay via $2\nu\beta\beta$ are known, with half-lives ranging from $\sim 10^{18}$ and $\sim 10^{22}$ years. This process preserves the leptonic number, is not significantly dependent on the neutrino mass and is not able to discriminate the neutrino nature: Dirac [112] or Majorana [113].

The Majorana model of the neutrino allows a SM forbidden decay: the *neutrinoless double beta decay* ($0\nu\beta\beta$, fig.3.7 right). This decay can not be realized within the SM because it violates the lepton number conservation by two. Such a process requires a Majorana mass component for the neutrino, whichever is the mechanism that generates it [114]. This is shown in fig.3.8: a mass term allows a chirality flip passing from $\bar{\nu}_e$ to ν_e . This way the antineutrino produced in a vertex become a neutrino that can be absorbed in the other interaction vertex, obtaining a $0\nu\beta\beta$ decay.

This decay has never been observed, consequently there are only lower limits on the half-life. Actually only a ten of isotopes between the possible ones are useful for this study: ^{48}Ca , ^{76}Ge , ^{82}Se , ^{96}Zr , ^{100}Mo , ^{116}Cd , ^{130}Te , ^{136}Xe and ^{150}Nd (for half-lives values see at [115] and [116] for more updated results on ^{76}Ge and ^{136}Xe).

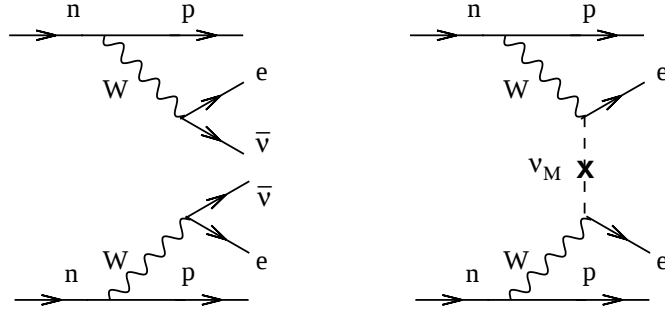


Figura 3.7: Double beta decay diagrams with two neutrino emission ($2\nu\beta\beta$) on the left and without neutrino emission ($0\nu\beta\beta$) on the right. The latter is possible only exchanging a Majorana neutrino.

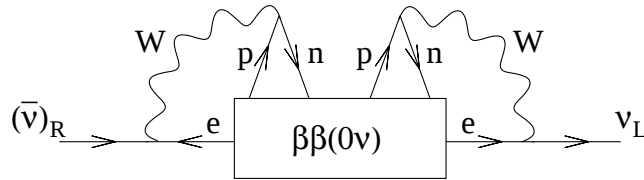


Figura 3.8: A $\bar{\nu}_e$ turns into a ν_e by means of a $0\nu\beta\beta$ interaction. This diagram proves that the eventual existence of the $0\nu\beta\beta$ decay implies the presence of a Majorana mass term for the neutrino.



Figure 3.9: CUORE-0 tower rendering and close up. Left: the $52 \times 5 \times 5 \text{ cm}^3$ TeO_2 crystals of 750 g each are disposed in 13 floors in groups of 4, for a total mass of 39 kg. The tower skeleton is made by ultra clean copper and the crystals are plugged to the frames by PTFE clamps. Right: close up of the tower during the assembly; crystals, copper structure and PTFE brackets (white components) are visible.

3.3.2 The detector

A first tower prototype of CUORE, named CUORE-0, is now in the final part of data taking and lasted about 2 years. It is composed by 52 crystals for a total mass of 39 kg of TeO_2 , and is hosted in the Cuoricino, its predecessor [117], cryostat in the Hall A of LNGS. As shown in fig.3.9 crystals are arranged in 13 floors in groups of 4 and are held to the copper structure (that act also as the heat sink of fig.3.1) by polytetrafluoroethylene (PTFE) brackets (the weak thermal coupling of fig.3.1). The typical base temperature of the cryostat is $13 \div 15 \text{ mK}$.

Each crystal is instrumented with a single NTD germanium thermistor for the signal readout and one silicon Joule heater for the offline correction of thermal gain drift, as described in sec.3.2.3, in fig.3.1 and in [118].

Particular attention was put into the selection and handling of the detector materials with the objective of minimizing the background contamination for CUORE-0. To reduce bulk and surface contamination of crystals during their growth, a radiopurity control protocol was developed in collaboration with the TeO_2 crystal producer at the Shanghai Institute of Ceramics, Chinese Academy of Science [119]. Only materials certified for radiopurity were used to grow the crystals. After production, the crystals were transported to LNGS at sea level to limit cosmogenic activation. Once they are arrived at the underground laboratory, a small number of them was mounted and operated as a bolometer for quality test. Contaminations from ^{238}U (^{232}Th) decay chain for bulk and surface are less than $6.7 \cdot 10^{-7} \text{ Bq/kg}$ ($8.4 \cdot 10^{-7} \text{ Bq/kg}$) and $8.9 \cdot 10^{-9} \text{ Bq/cm}^2$

($2.0 \cdot 10^{-9}$ Bq/cm²) at 90% C.L., respectively [120]. Material check of small parts, including NTD thermistors and silicon heaters, indicates that their radioactive content contributes to less than 10% of the total background in the $0\nu\beta\beta$ decay region of interest (ROI).

The Cuoricino experience tells that the most significant background for the measurements comes from smeared α particles originated in the tower frame and the surrounding cylindrical thermal shield, that leaves only a part of their energy in the crystals. All these components are made from radiopure electrolytic tough pitch copper [121]. A different tower geometry with respect Cuoricino allowed a reduction by a factor 2.3 and 1.8 for total copper mass and surface area, respectively. Monte Carlo simulations predict a factor of 1.3 decrease in α background from the thermal shield arriving at the crystals due to the change in the disposal [122]. In addition, different surface treatments were tested to further reduce the copper contaminations [123]. Among them a series of tumbling, electropolishing, chemical etching, and magnetron plasma etching for the surface treatment was selected. After these processes the measured surface contaminations are $1.3 \cdot 10^{-7}$ Bq/cm² 90% C.L. for ²³⁸U and ²³²Th [123].

The CUORE-0 detector assembly procedure was designed to minimize the recontamination of clean components. Tower mounting takes place in a dedicated class 1000 clean room in Hall A of the LNGS underground facility. To reduce radon (and its progeny) exposure of components, all the assembly was performed under nitrogen atmosphere inside glove boxes [124]. All the tools inside the glove boxes, in particular those who touch the tower components, were cleaned and certified for radiopurity. Then, as already said, the completed tower was enclosed in copper thermal shield and then inserted in the Cuoricino cryostat. To minimize exposure to the environment during this operation, mounting was performed in the Cuoricino clean room, and the tower was kept under nitrogen flux for as long as possible.

CUORE-0 uses for the first time flexible printed circuit board (PCB) cables and *in situ* wire bonding for electrical wiring of the tower. This is one of the major upgrades that significantly improved the robustness of bolometer readout wiring, compared to the Cuoricino design. A series of flexible PCB cables with copper traces [125, 126] was attached to the copper frame from the bottom plane to the top. The lower ends of these cables were bonded to the metal pads of thermistors and heaters with 25 μ m diameter gold wires. The upper ends were connected through flexible PCB at the 10 mK plate to a set of Manganin twisted pair flat ribbon cables running un-interrupted to the feedthroughs on the top plate of the cryostat. If on one side PCB cables of course improves the robustness and the reproducibility of the assembly, on the other side they could potentially affect the noise and thermal behavior of the array. In any case the negative effects are under control and possible means to mitigate them have been identified. Overall, only 3 bolometers (6%) are not fully functional from the loss of one thermistor and two heaters. The two heater-less bolometers can be used in non-standard analysis with thermal gain correction based on model presented in [127], but anyhow they will not be taken into account in the work presented in this thesis.

CUORE-0 is operated in the same cryostat, uses the same external lead and borated-polyethylene neutron shielding, and is enclosed in the same Faraday cage that was used for Cuoricino. The front-end electronics [128, 129, 130] and data acquisition hardware are also identical to those used in Cuoricino. A new algorithm is implemented to automatize the correct working point search (see sec.3.2.3), that scans different voltages until the best SNR is obtained for every single channel. Bolometers signals are amplified and filtered with a six-pole Bessel low pass filters. Subsequently, signals are digitized by two 32-channel National Instruments PXI analog-to-digital converters with a 125 S/s sampling rate, 18-bit resolution, and 21 V full scale. All samples are both triggered and stored continuously on disk, in such a way that data can be reprocessed and triggered in a second moment, eventually with a different trigger. During triggering (in real time or during reprocessing) for every trigger fire a window with 626 sampling points (5.008 s), including a pretrigger segment of 125 samples, is saved, as indicated in fig.3.5. Each bolometer has an independent trigger threshold. As explained in sec.3.2.3 one of the heater function is to stabilize the amplitude variation due to temperature instability of the cryostat. To this end each 300 s a pulse of constant energy is released from the heater (also called pulser for this reason). Finally, a baseline trigger identifies a baseline pulse every 300 s to provide snapshots of the detector working temperatures and noise spectra.

CUORE-0 data taking is subdivided into “datasets”. Each dataset consists in a series of initial calibration runs, some background runs and a set of final calibration runs. Calibration runs are done to calibrate the channel spectra using known energy peaks from ^{232}Th decay chain, with energy ranging from 511 to 2615 keV. The source consists in two thoriated tungsten wires with activity of 50 Bq and is positioned into two vertical tubes on opposite sides of the tower that run between the outer vacuum chamber and the external lead shielding. Background refers to data acquired without calibration sources and with data good for physics analysis as DM and $0\nu\beta\beta$ decay search; generally a background run lasts 24 h. The signal rates on each bolometer for the calibration and background data acquired with the standard trigger are $60 \div 70$ and $0.5 \div 1.0$ mHz, respectively.

3.3.3 Collected statistics

CUORE-0 started to take data in March 2013 and had some interruptions for cryostat maintenance. In fig.3.10 it is shown the duty cycle from the beginning up to March 2015. As it can be seen there is a large stop from the end of August 2013 to the second half of November 2013 for an important cryostat maintenance, after which baseline and peaks resolution improved considerably. In fact, dividing acquired data into these two phases and considering single channels, the median noise full width at half maximum (FWHM) at the baseline in background runs before and after the long cryostat maintenance are 3.9 and 2.6 keV, respectively. Due to this reason in this thesis only data from November 2013 will be considered. The list of used datasets with relative start and stop

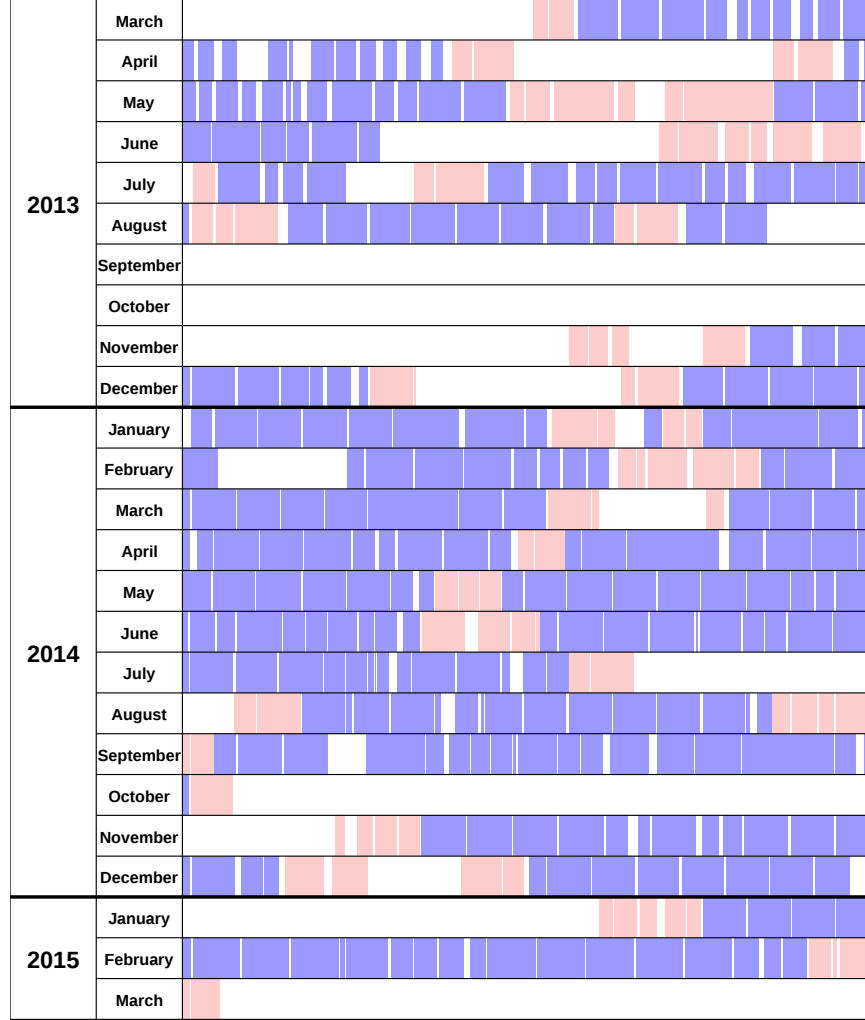


Figure 3.10: CUORE-0 duty cycle. The data taking started in March 2013 and ended in March 2015. Blue indicates background runs, while red indicates the calibration ones. In the period August-September 2013 a large cryostat maintenance took place, after which baseline and peaks resolutions improved substantially. In this thesis only data taken after this operation will be used for the analysis.

Dataset	Start Time UTC	Stop Time UTC	Background [d]	Calibration [d]
2079	13-11-17 20:41	13-12-11 13:05	8.72	2.68
2085	13-12-20 18:03	14-01-20 11:46	23.22	5.12
2088	14-01-17 16:56	14-02-24 10:57	18.03	9.26
2091	14-02-18 17:40	14-03-19 18:24	19.40	7.14
2097	14-03-24 14:55	14-04-17 17:30	18.04	2.71
2100	14-04-15 17:07	14-05-15 09:30	21.24	4.62
2103	14-05-12 11:01	14-06-13 08:17	22.77	4.38
2109	14-06-13 23:00	14-07-21 09:24	27.48	5.09
2124	14-08-29 17:32	14-10-03 08:30	23.21	5.00
2130	14-11-07 16:48	14-12-09 09:10	17.49	4.69
2139	15-01-19 18:36	15-03-02 17:23	18.97	4.48

Table 3.1: List of datasets used in this analysis with relative start and stop time. Start and stop are the start and the stop time of the first and of the last calibration run, respectively. Background and calibration indicates the average live time for each dataset of this kind of run. In this second phase of the experiment there are two additional datasets (2118 and 2133) that are not take into account since they closed unexpectedly without a n-pulser measurement (see sec.4.4).

time is in tab.3.1.

When acquired data quality is low it is possible to set “bad intervals”, meaning that these intervals are not good for the analysis. The intervals selection is performed channel by channel looking at baseline resolution, baseline stability, noise during run, electronic problems and in general everything that worsens the measure. Consequently the total exposure is given by the sum of single channel live times. The accumulated exposure is $24.7 \text{ kg} \cdot \text{y}$ (corresponding to $6.9 \text{ kg} \cdot \text{y}$ of ^{130}Te isotopic exposure, removing all the bad intervals, updated to October 2014). The energy calibration is performed with a second order polynomial fit in the energy range $0 \div 2.6 \text{ MeV}$, to account for a small non-linearity that drives at a 10 keV discrepancy at the 2615 keV peak.

In the $0\nu\beta\beta$ decay ROI the cuts efficiency correspond to $89.7 \pm 0.9\%$. Geant4 simulations showed that the probability of the $0\nu\beta\beta$ decay electrons to be fully contained in a single crystal is equal to $87.4 \pm 1.1\%$. Considering the $99.00 \pm 0.01\%$ trigger efficiency, measured on pulser events near the ROI (see sec.4.4), the total detection efficiency of CUORE-0 in the $0\nu\beta\beta$ decay region is $77.6 \pm 1.3\%$ [131] (numbers update to the end of May 2014). This result is close to the one obtained for Cuoricino: $82.8 \pm 1.1\%$ [117]. For a more detailed explanations of the the event selection and the quality cuts done in the $0\nu\beta\beta$ decay ROI look at [132].

One of the most great result obtained from CUORE-0 is the reduction of the background counts due to contaminations. As can be seen in fig.3.11, where a comparison of the two spectra is shown in the range $300 \div 7500 \text{ keV}$, the

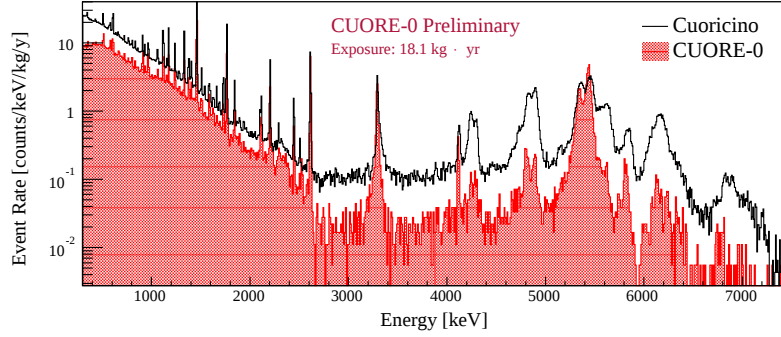


Figure 3.11: CUORE-0 (red shaded) and Cuoricino (black) background spectra comparison. The improvements in CUORE-0 are evident along all the energy interval that goes from 300 to 7500 keV: ^{238}U γ lines reduced by a factor 2 (better radon control), ^{232}Th γ lines not reduced (originated from the cryostat); ^{238}U and ^{232}Th α lines reduced thanks to the new detector surface treatment. The CUORE-0 spectrum present in this image is made by data taken from March 2013 to middle May 2014.

CUORE-0 spectrum is constantly lower than the Cuoricino one. In particular ^{238}U γ lines are reduced by a factor 2 due to better radon control, ^{238}U and ^{232}Th α lines are reduced thanks to the new detector surface treatment, while ^{232}Th γ lines are not reduced since they are originated from the cryostat (the CUORE one is designed to decrease this effect).

More precisely in the $0\nu\beta\beta$ decay ROI the background rate is equal to 0.063 ± 0.006 counts/keV/kg/y in CUORE-0 and 0.153 ± 0.006 counts/keV/kg/y in Cuoricino crystals with dimensions of $5 \times 5 \times 5 \text{ cm}^3$, while for the whole detector is 0.169 ± 0.006 counts/keV/kg/y. The reduction of the α background is evaluated in the region that goes from 2.7 to 3.9 MeV excluding the ^{190}Po peak in the range $3.1 \div 3.4 \text{ MeV}$. In this interval, the so-called α flat continuum region, CUORE-0 reached a background rate of 0.020 ± 0.001 counts/keV/kg/y, which is almost 6 times smaller than the Cuoricino result of 0.110 ± 0.001 counts/keV/kg/y.

These encouraging results imply that the more rigorous copper surface treatment, the improved crystal production and treatment protocols, and the more stringent assembly procedures in the clean environment have been extremely effective in the background reduction aim. Thanks to this, CUORE-0 is expected to reach a $0\nu\beta\beta$ sensitivity larger than the Cuoricino one of $2.6 \cdot 10^{24} \text{ y}$ at 90% C.L. in about 1 year of live time.

By means of its larger array, that allows a more powerful time coincidence analysis and a more effective self-shielding from external backgrounds, CUORE will be able to reach the background goal of 0.01 counts/keV/kg/y, that corresponds to a 90% C.L. sensitivity of $9.5 \cdot 10^{25} \text{ y}$ for 5 years of live time [133].

Chapter 4

Optimum Trigger: the low energy trigger

4.1 Introduction

In order to be able to observe a DM interaction in CUORE-0, a low energy trigger is needed. In fact, the standard trigger used in CUORE-0, the Derivative Trigger, has an extremely small detection probability an event below 30 keV. Given the very low event rate and sampling frequency in such experiment it is possible to use a trigger which is software generated. Using a trigger and a pulse shape algorithm based on the matched filter technique, which removes the non physical pulses, it has been demonstrated that is possible to push the energy threshold down to a few keV [134]. Such trigger, named Optimum Trigger (OT), uses a transfer function that maximizes the SNR and is directly applied to the data flow coming from the detector.

In the following the Optimum Trigger with its characteristics and the algorithm on which is based will be presented.

4.2 Optimum Filter

The Optimum Filter (OF) is the algorithm which OT is based on. This filter evaluates the amplitude of a pulse maximizing the SNR. To work it is based on the assumption that a detector waveform $y(t)$ can be written as:

$$y(t) = A \cdot s(t) + n(t) \quad (4.1)$$

where $s(t)$ is the known signal time evolution, A the signal amplitude and $n(t)$ the detector noise, which is stationary. The first addend indicates that the signal shape is independent from the amplitude, meaning that it is independent from the event energy. The last assumption is that the noise has a known power spectrum, defined by:

$$N(\omega) = \langle n(\omega)n(\omega^*) \rangle$$

where $n(\omega)$ is the Fourier transform of $n(t)$ and $\langle \rangle$ denotes the expectation value over a large number of noise waveforms. Given that the filter works on sampled data, the eq.(4.1) can be written as:

$$y_i = A \cdot s_i + n_i \quad (4.2)$$

with i sample index.

Now the filter will be derived for the white noise case and then for the general noise case.

4.2.1 White noise case

The white noise is a noise with a time independent Gaussian distribution. The likelihood to maximize with the filter as a function of the displacement j between the template s and the signal in y is

$$L_j(y_i|A_j) = \prod_i \frac{1}{\sqrt{2\pi}\sigma} \exp \left[-\frac{(y_i - A_j s_{i-j})^2}{2\sigma^2} \right] \quad (4.3)$$

where σ is the noise RMS and the product extends over the length of y_i . In the numerator of the exponential is present a $-j$ in the subscript of s since the assumption is that the registered signal is scaled (property described by A_j) and shifted from the known one. So, for each shift j , one can impose:

$$\frac{d}{dA_j} L_j(y_i|A_j) \propto \sum_i (y_i - A_j s_{i-j}) s_{i-j} = 0.$$

The solution for the amplitude A_j is

$$\hat{A}_j = \frac{\sum_i y_i s_{i-j}}{\sum_i s_{i-j}^2}. \quad (4.4)$$

To evaluate the delay j it is possible to take the numerator of eq.(4.3), $\sum_i (y_i - A_j s_{i-j})^2$, and substitute the solution just found for A_j . Before doing this, it is useful to expand the square, that must be minimized:

$$\sum_i (f_i + n_i)^2 + A_j^2 \sum_i s_{i-j}^2 - 2A_j \sum_i f_i s_{i-j} - 2A_j \sum_i n_i s_{i-j}. \quad (4.5)$$

where we used the eq.(4.2) and for simplicity $y_i = f_i + n_i$ (meaning that $f_i = A_j \cdot s_{i-j}$). The first and the last terms can be removed since they have no influence on the result, given that they are constants: the first because the

measured signal is given and the last because the noise is uncorrelated and with 0 means. Now, changing the signs, the sum to maximize is:

$$2A_j^2 \sum_i f_i s_{i-j} - A_j^2 \sum_i s_{i-j}^2 = A_j^2 \sum_i s_{i-j},$$

that, replacing A_j , becomes

$$\frac{\left(\sum_i y_i s_{i-j} \right)^2}{\sum_i s_{i-j}^2}.$$

Using the Cauchy-Swartz inequality, it results $\left(\sum_i y_i s_{i-j} \right)^2 \leq \sum_i y_i^2 \cdot \sum_i s_{i-j}^2$. The equality sign is possible only if $s_{i-j} = cy_i$, with c numerical constant. So the maximum position for the filtered pulse is obtained for $j = 0$, and the filtered signal will be shifted of $-i_M$, where i_M is the maximum position of the template.

Coming back to eq.(4.4) it is possible to rewrite the filtered amplitude y'_i as a convolution of the “kernel” K_i of the filter and the original waveform y_i :

$$y'_i = y_i \otimes K_i \quad (4.6)$$

$$K_i = \frac{s_{-i}}{\sum_l s_l^2}.$$

The filter leaves the pulse amplitude unmodified, while the noise RMS is reduced to

$$\sigma'^2 = \frac{\sigma^2}{\sum_l s_l^2}. \quad (4.7)$$

To align the maxima of the two signals the kernel can be shifted of $-i_M$. In the frequency domain the eq.(4.6) can be written as:

$$y'(\omega_k) = y(\omega_k) \cdot K(\omega_k) \quad (4.8)$$

that becomes

$$y'(\omega_k) = y(\omega_k) \cdot K(\omega_k) e^{-j\omega i_M}$$

including the delay of the filtered maximum.

From this equation it is possible to obtain the filter transfer function:

$$H(\omega_k) = K(\omega_k) e^{-j\omega i_M} = \frac{1}{E_s} s^*(\omega_k) e^{-j\omega i_M} \quad (4.9)$$

where E_s is the signal energy, defined as $E_s = \sum_l s_l^2$.

4.2.2 General noise case

When the noise is correlated, the elements of the product in eq.(4.3) are no longer independent. This means that the filter in eq.(4.9) cannot be used as it is. Applying a “whitening” filter like

$$W(\omega_k) = \frac{1}{n(\omega_k)}$$

to the noise it is possible to use the equations presented in the previous section. This filter has to be applied to the combination signal + noise (*i.e.* to y_i), so the signal shape is modified into $s(\omega_k)/n(\omega_k)$ and the transfer function becomes

$$H(\omega_k) = h \frac{s^*(\omega_k)}{n^*(\omega_k)} e^{-j\omega_i M} \frac{1}{n(\omega_k)} = h \frac{s^*(\omega_k)}{N(\omega_k)} e^{-j\omega_i M} \quad (4.10)$$

where h is a normalization constant that leaves unmodified the signal amplitude after the filter:

$$h = 1 / \sum_k \frac{|s(\omega_k)|^2}{N(\omega_k)}.$$

The new noise power spectrum is

$$N'(\omega_k) = h^2 \frac{|s(\omega_k)|^2}{N(\omega_k)}$$

and the new noise RMS is

$$\sigma'^2 = \sum_k N'(\omega_k) = h. \quad (4.11)$$

In the case of white noise, the input power spectrum is given by

$$N(\omega_k) = M\sigma^2$$

where M is the window length. Always in this case eq.(4.11) reduces to

$$\sigma'^2 = \sigma^2 \frac{M}{\sum_k |s(\omega_k)|^2},$$

that, using the Parseval identity, can be demonstrated to be equal to eq.(4.7).

4.2.3 Filter transfer function

Passing from eq.(4.6) to eq.(4.8), and then to eq.(4.10), the discrete convolution theorem has been implicitly used. In fact the theorem says that if a signal s_i is periodic with period M , then its discrete convolution with a kernel H_i of finite duration M is a member of the discrete transform pair:

$$\sum_{j=0}^{M-1} s_{i-j} H_j \iff s(\omega_k) \cdot H(\omega_k).$$

To apply this theorem the two conditions in the hypothesis must be fulfilled: The kernel and the signal must have the same duration and the signal must be periodic. The first condition is simple, it only requires to add some zeros to the kernel until it reaches the signal length. The second condition is needed because the Discrete Fourier Transform (DFT) works on periodic windows of finite length. This because the DFT frequency spectrum is the spectrum of an infinite repetition of the input window. If the input data are not periodic it happens that the filter would pollute the right side of the filtered signal with the left part of the original sampled data (and vice versa). This way the only part of unspoiled signal is the one that corresponds to the zeros of the kernel (see fig.4.1).

To accomplish the hypothesis, the transfer function has been build following these steps:

1. build the OF transfer function $H(\omega_k)$ of length M using the signal s_i and the noise power spectrum $N(\omega_k)$, both of length M ;
2. transform $H(\omega_k)$ in the time domain by means of DFT, obtaining the kernel H_i of length M ;
3. insert M zeros in the middle of H_i , obtaining the new kernel H_i^d of length $2M$;
4. smooth H_i^d in proximity of the zeros to get the new smoothed kernel H_i^{ds} ;
5. transform H_i^{ds} into the frequency domain, obtaining the $H_i^{ds}(\omega_k)$, always of length $2M$.

The fourth point is needed to avoid the Gibbs phenomenon: if H_i^d does not approaches zero in the central part of the kernel, where zeros are, a discontinuity will be created in the filtered signal, introducing fake oscillations in the DFT transform. This means that only the central part of length M of the filtered samples will be correctly filtered, the firsts and the lasts $M/2$ points will be spoiled, as described in fig.4.1. In CUORE-0 the smoothing is (will be) done using the cosine function. In particular the quarter-period that goes from one to zero for the firsts $M/2$ samples and the quarter-period that goes from zero to one for the lasts $M/2$ points are used.

To correctly filter all the data flow from the detector, concatenated windows of length $2M$ should be taken, where the overlap is equal to $M/2$ with the preceding and following windows, as indicated in fig.4.2.

In practice the filter is implemented using the the average pulse of a channel as s_i and the average noise power spectrum of the same channel as $N(\omega_k)$. As described, the cosine has been selected as smoothing function, so the first half of the filter can be written as:

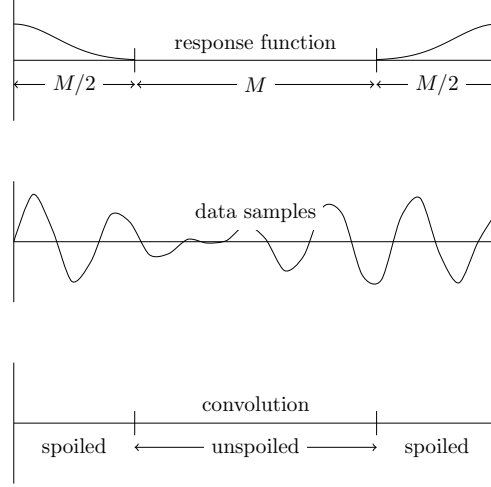


Figure 4.1: The filter kernel is composed by a central part of zeros and by two external bands. The central part of length M , equal to the length of the signal to filter, correctly transforms the data samples. In the external parts, of length $M/2$, the data samples are spoiled when filtered (the left side with data from the right side and vice versa).

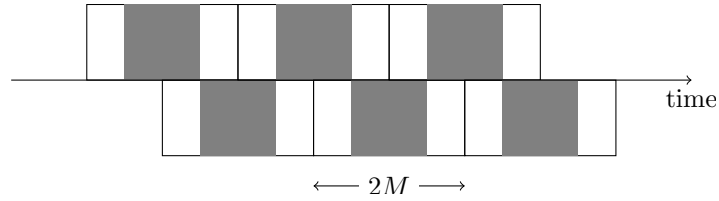


Figure 4.2: The data flow is divided into concatenated windows, each is $2M$ length. The overlapping is needed to bypass the Gibbs problem: only the central (grey) part is correctly filtered, instead the external (white) ones are not. The central part is long M , while both the external bands $M/2$.

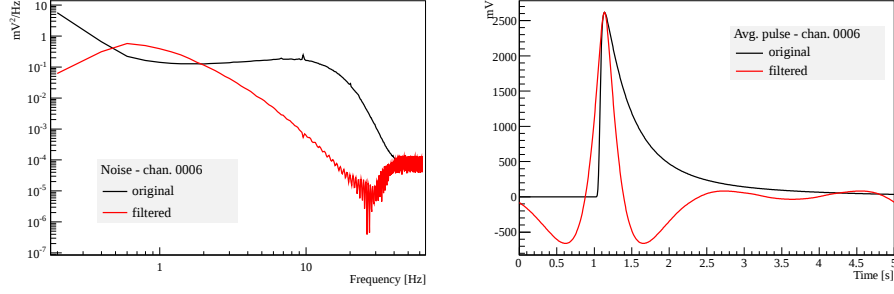


Figure 4.3: Average noise power spectrum (left) and average pulse (right), original in black and filtered in red, of channel 6 in dataset 2088. As can be seen the filtered average pulse shows a quasi-symmetric shape and a zero baseline. The acquisition windows are 626 samples long, corresponding to 5.008 s. Since the window length is not doubled, only its central part is correctly filtered.

$$\begin{aligned}
 H_i^{ds} &= H_i^d \quad , \quad i < \frac{M}{2} - L \\
 H_i^{ds} &= \frac{H_i^d}{2} \left\{ 1 + \cos \left(\frac{\pi}{L} \left[i + 1 - \left(\frac{M}{2} - L \right) \right] \right) \right\} \quad , \quad \frac{M}{2} - L \leq i < \frac{M}{2} \\
 H_i^{ds} &= H_i^d = 0 \quad , \quad \frac{M}{2} \leq i < M
 \end{aligned}$$

where L is the cosine half-period. The second half is identical to the first, but mirrored. Once H_i^{ds} has been calculated, the transfer function in the frequency domain $H(\omega_k)$ can be applied to the data. In fig.4.3 are shown the average noise power spectrum on the left and the average pulse on the right, original (black) and filtered (red), of channel 6 in dataset 2088. Looking at the second image it is evident that the filtered pulse presents an almost symmetric shape and a zero baseline.

4.3 Optimum Trigger

As mentioned in sec.3.3.2, the continuous data flow from the detector is saved on disk, in such a way that it can be reanalyzed in a second moment. Reprocessing it with the OT, the data flow is divided into concatenated windows, as shown in fig.4.2, where the trigger can fire only in the central part. The name Optimum Trigger comes from the fact that trigger works on samples filtered with the Optimum Filter.

Looking at data filtered with the OF in fig.4.4 it is evident that:

- noise fluctuations are reduced;

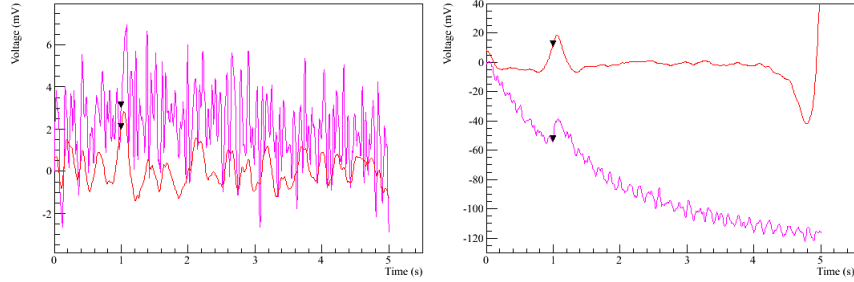


Figure 4.4: Left: a 4 keV (left) and a 18 keV (right) events triggered with the OT, original pulses in blue, filtered ones in red. In both cases it is possible to see that filtered samples are less noisy: baseline oscillations are smaller and frequencies that do not belong to the signal are suppressed. The image on the right shows that the OF removes the baseline inclination. It shows also the Gibbs problem, recognizable in the steep slope at the very end of the filtered pulse. Triangles indicate the trigger position.

- the baseline has zero mean;
- the filter is sensitive to the signal shape, suppressing pulses with a shape different from the expected one.

All of this allows to lower the energy threshold with respect a trigger that works with non-filtered data.

OT fires when pulse height exceed a threshold and a local maximum is found within a FWHM of the filtered ideal pulse (the average pulse). The threshold is channel-dependent, and is set equal to a given number of sigma n_σ of filtered noise σ_{OF} , which is known *a priori* (eq.(4.11)). Data presented here are triggered with $n_\sigma = 3$, meaning that the threshold is equal to $3 \times \sigma_{OF}$. Once the trigger fires, it will be possible to set a new trigger flag only after an interval, which length is equal to a FWHM of the filtered ideal pulse. The trigger position is then shifted back of a fixed quantity, equal to the time that elapses between the middle of the rise and the maximum of the non-filtered average pulse. This because during data analysis the trigger flag is expected to be before the pulse maximum. In all figures with triggered pulses (as in fig.4.4) the triangles represent the trigger position.

When an high energy event occurs (and is triggered), its filtered samples may present a set of side pulses due to OF action. These fake pulses can exceed the threshold and make the trigger fire again. In the old version of the OT this problem was solved by putting a veto region on the sides of the primary pulse, where it is not possible to set a trigger (see fig.4.5). Clearly the veto becomes an important source of inefficiency, in particular when contaminations with high energy peaks are present (like ^{210}Po or ^{210}Pb), since the high energy peaks rates produce a lot of dead time.

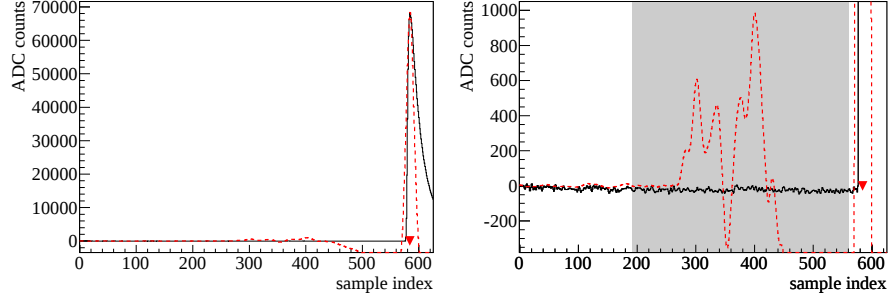


Figure 4.5: Left: an high energy pulse (5.4 MeV) is triggered. Right: side lobes of the filtered pulse can exceed the trigger threshold. To avoid to trigger this fake pulses, in the old version of the trigger a veto region is set (gray band): in this region it is not possible for the trigger to fire. In both images black continuum line for the original pulse, red dashed line for the filtered one.

In the new version of the trigger, veto regions are removed. Side pulses are not triggered by checking that, in the vicinity of them, there is not an higher pulse that can generate them as side lobes. This evaluation is based on the average filtered pulse shape, since the number and the distance of side lobes change channel by channel. An example of this is in fig.4.6, where it is shown what the trigger sees: the grey bands are the regions where is not possible to make the trigger fire and the orizzontal red line is the threshold. In the window is present an high energy pulse and it is evident that also two side lobes per side exceed the threshold, but anyway they are not triggered.

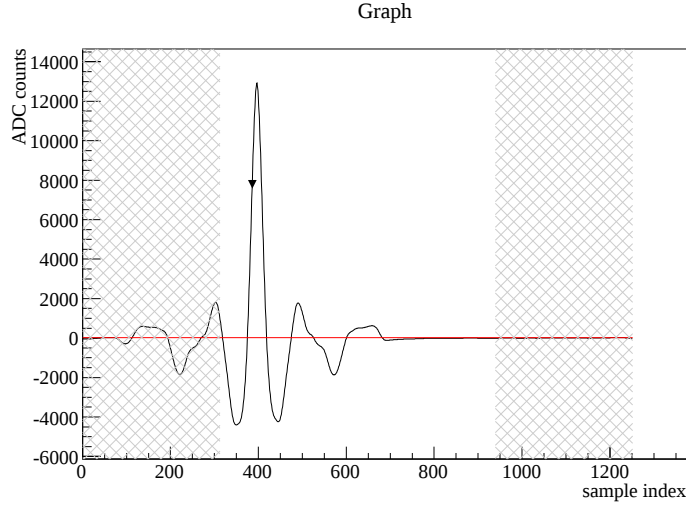


Figure 4.6: Trigger window with an high energy pulse. The grey bands are the regions where it is not possible to set a trigger, while the red orizzontal line represents the threshold. As can be seen on the sides of the pulse there are lobes higher than the threshold, that anyway are not triggered thanks to the new implementations of the OT.

Another new OT feature is to do not trigger deep pulses anymore (example given in fig.4.7). The simplest way to understand why they may make the trigger fire is to look at a normal pulse, as in fig.4.6, and imagine to turn it upside down. At this point the lower oscillations, introduced by the OF, that now are on the top, can be high enough to exceed the threshold. To avoid this is performed a check, similar to the one done for the side lobes, that controls that the event has not been generated by the filtering of a deep pulse.

Compared to traditional algorithms, this trigger is much more powerful, but requires the knowledge of the average pulse and of the noise power spectrum of each channel. Consequently it cannot be used at the beginning of the data taking, since at least a long measurement is needed to estimate the average pulse and the noise power spectrum. After this first runs, it can be used as standard trigger, without reprocessing the continuous data saved on disk.

4.4 Trigger efficiency

At high energy the trigger efficiency (standard and OT) can be measured with a single pulser at few MeV. The idea is to evaluate efficiency as the number of triggered heater pulses over the number of fired heater pulses. The value obtained can be used on a large energy range that extends down to ≈ 100 keV, well below the ROI of $0\nu\beta\beta$ decay. Dealing with low energies this approach no

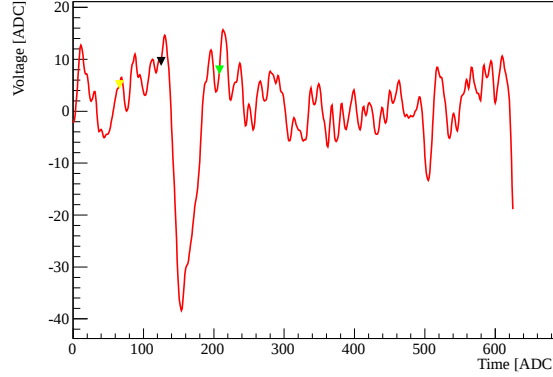


Figure 4.7: Example of a deep pulse. This kind of event can make the trigger fire, so in the new version of the OT a dedicated check is implemented to avoid this.

longer works, because going toward 0 keV the trigger efficiency goes to 0. In the OT case, the characteristic width of this efficiency transition is given by the filtered baseline resolution, as explained later.

In this scenario, a measure on a single pulser is not sufficient to estimate the trigger efficiency and a dedicated run is needed. This dedicated run takes the name of *n-pulsers* measurement, where a set of many heaters pulses are used, in such a way to study the efficiency as a function of energy. The DAQ system sets a pulser flag every time that the heater fires. A heater pulse is considered detected if is present a trigger in a 100 ms window from the DAQ flag. Then the efficiency ε is evaluated as the ratio of the triggered over the total fired heater pulses and the error is estimated using the formula

$$\sqrt{\frac{\varepsilon(1 - \varepsilon)}{N}}$$

where N is the number of pulses fired from the heater for that energy.

As mentioned in sec.3.3.2, each time that a group of crystals were delivered from the producer some of them were operated as bolometer to check that they match the required quality. In one of these measurements, the Cuore Crystals Validation Run 2 (CCVR2), the first version of the OT was tested. A 2-days n-pulsers run was acquired and two Monte Carlo simulations were performed to validate the obtained results. The two Monte Carlo were carried out with the method described in [127]:

- a run with simulated heater pulses, generated with a flat spectrum between 1 and 50 keV, intended to validate the Monte Carlo. The time interval between two consecutive heater pulses was 25 s, like in the n-pulsers measurement;

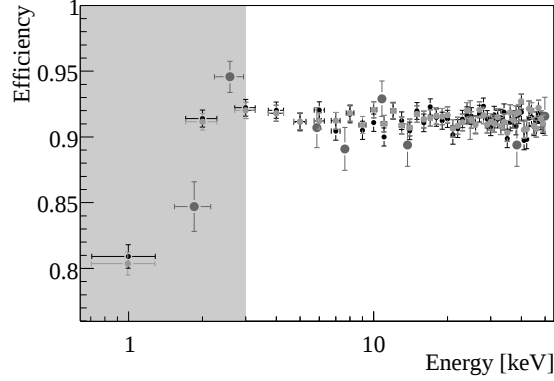


Figure 4.8: Detection efficiency on a CCVR2 channel. Particle Monte Carlo in black circles, heater Monte Carlo in green circles, heater scan data in big red circles. The grey band represents the region discarded for data analysis. The other CCVR2 channels show a similar behavior.

- a run with simulated particle pulses, generated with a flat spectrum between 1 and 50 keV, intended to evaluate the particle efficiencies. The time interval between two consecutive pulses was 25 s, like in the n-pulsers measurement.

The Monte Carlo runs included simulated noise, generated from noise power spectrum of n-pulsers measurement, and particle events background, randomly generated from the CCVR2 energy spectrum and the measured event rate. In fig.4.8 are shown the Monte Carlo results (both) compared to the n-pulsers measurement: black circles for particle Monte Carlo, green circles for heater Monte Carlo and big red circles for heater scan. The grey band was discarded from the subsequent analysis because of OT amplitude estimator bias due to negative noise fluctuations that lower the pulse amplitude. Similar results holds for the other CCVR2 channels.

From this graph two conclusions must be taken: the Monte Carlo and the measured n-pulsers are compatible, validating the simulation results, and the trigger behavior on heater and particles is similar, demonstrating that the OT acts in the same way on pulser and particles.

Efficiency reaches a constant value around 90% due to ^{210}Po contaminations and to the presence of the veto in the old version of the OT. Given its half-life of around 140 days, ^{210}Po is not a problem for CUORE-0.

Starting from July 2013 a n-pulsers measurement is carried out in each dataset of CUORE-0, to study the bolometers efficiency at low energy. Originally was proposed to perform more than one measurement per dataset, in such a way to have as much checks as possible of detector behavior. Thanks to the fact that subsequently was found a way to describe the efficiency slope, the runs

number was lowered to one per dataset. At a first thought, one might expect a sharp slope for the efficiency as function of energy: if the pulser energy is smaller than the threshold this would not be triggered, on the contrary if it is larger it would be triggered, with efficiency directly passing from 0 to 1. The correct way to describe the trend is to consider that the pulser peaks have a non-zero width, given by the energy resolution. Consequently the right (left) tail of a pulser peak could exceed (be below) the energy threshold and be triggered (not be triggered) leading to a intermediate efficiency.

Given this, the OT efficiency is expected to have a Gaussian cumulative density function and can be predicted with *a priori* informations. Using the error function (erf), efficiency ε at energy E is:

$$\varepsilon(E) = \frac{1}{2} \operatorname{erf} \left(\frac{E - \theta}{\sqrt{2}\sigma_{OF}} \right) + \frac{1}{2}$$

where σ_{OF} is the OF resolution and θ is the OT threshold, in this case imposed to be equal to $3 \times \sigma_{OF}$, both defined in the previous section. It is important to specify that the energy spectrum threshold is not mandatorily equal to the OT threshold, but it can be different and, for example, set equal to the value at which the 99% efficiency is reached, while at θ it is evident that efficiency is always equal to 50%. Fig.4.9 shows an n-pulsers measurement result for channel 37 of CUORE-0, with superimposed the corresponding erf, while the vertical line named OT threshold indicates the θ of the previous formula. In the upper part of the image there are the residuals between the theoretical curve and the experimental points.

The reason why no more than a single n-pulsers measurement is needed per dataset, is that by using the error function, it is possible to evaluate the efficiency at any energy for each run. Indeed, taking the average pulse and the average noise, it is possible to monitor run by run the filtered baseline resolution and the efficiency at the selected threshold. The former is possible applying the OF to the noise of the run. The latter is possible using the erf with the baseline resolution and the OT threshold corresponding to the selected run (σ_{OF} and θ of previous formula) and then looking at the efficiency for the chosen spectrum energy threshold. Predictably the more the resolution is small (good), the more the efficiency is high (for a fixed energy), as can be seen in fig.4.10.

4.5 Trigger application

OT effectively presents better results with respect the standard trigger, the Derivative Trigger. The working principle of this is explained in fig.4.11 and is very simple: the difference in the signal amplitude of two samples at a fixed time distance (average) is compared with a reference value (threshold); if this quantity is bigger than the reference value for at least a given number of consecutive samplings, a trigger flag is set in the data stream on the first sample that exceeded the threshold. Also in this case the trigger is software generated revealing to be simple to be optimize channel by channel.

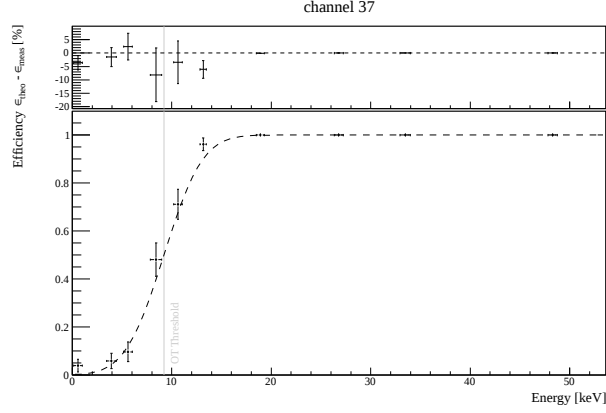


Figure 4.9: OT trigger efficiency for channel 37 as a function of energy, measured in a dedicated n-pulsers run in CUORE-0. In the lower part of the graph, points represent the measured efficiency obtained by the ratio $\frac{\text{triggered pulses}}{\text{fired pulses}}$, the dashed black line is the expected efficiency trend given by the erf and the vertical gray line is the OT threshold (50% efficiency by definition). In the upper part of the graph are shown the residuals.

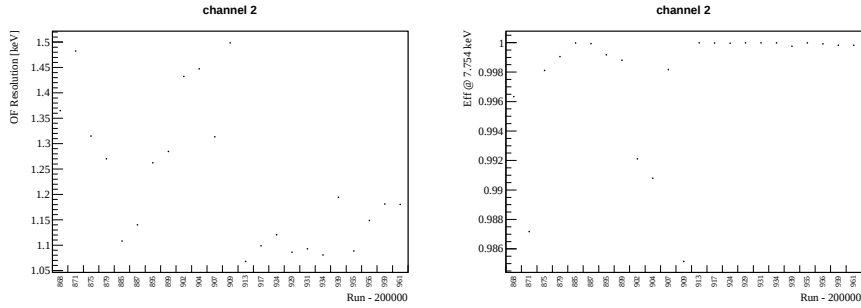


Figure 4.10: Left: Using the average noise of each run it is possible to monitor the OF baseline resolution run by run during data taking (channel 2 in the example). Right: taking this resolution it is possible to estimate, by the erf, the trigger efficiency at a given energy (typically the threshold selected for that channel during the n-pulsers run analysis, in this case the channel 2).

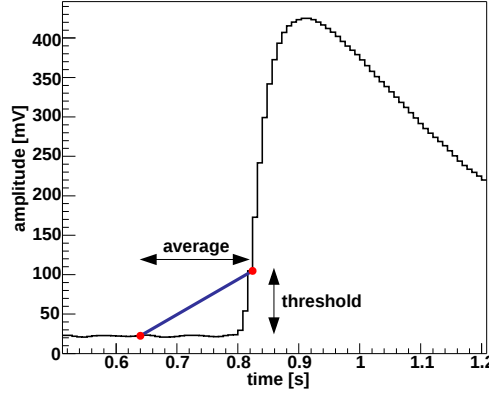


Figure 4.11: Derivative Trigger working principle. The trigger fires when the amplitude difference between two points at a fixed time distance (average) is larger than a reference value (threshold) for a given number of samples. Being a software generated trigger, it can be easily optimized channel by channel.

In fig.4.12 it is shown a comparison of the two triggers used in CUORE-0, OT in red and Derivative in black. On the left there are the experimental points from two different n-pulsers runs for channel 2 (circles for OT, squares for Derivative), one run per trigger kind. On the right are presented the 90% efficiency threshold distributions (continuous line for OT, dashed for Derivative). It is important to underline that in both cases the 90% efficiency threshold is evaluated from the erf, but for the OT the curve is given from *a priori* informations, instead for the Derivative is the result of a fit. The OT energy threshold lowering is evident.

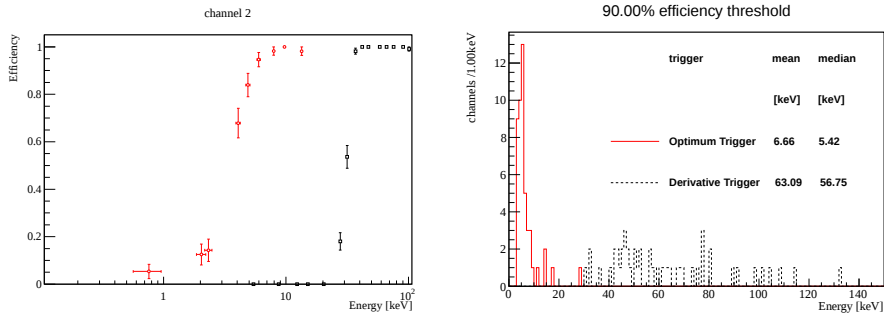


Figure 4.12: Left: scatter plot efficiency vs energy for Optimum (red circles) and Derivative (black squares) triggers for channel 2 of CUORE-0 in dataset 2088. Right: thresholds distribution for the Optimum (continuous line) and the Derivative (dashed line) triggers in dataset 2109. The threshold in this case is defined as the 90% efficiency resulting from the erf. For the OT the erf parameters are evaluated from the NPS, for the Derivative are the result of a fit.

Finally to validate the improvements of the OT it is possible to simply compare the differences between the two energy spectra. In fig.4.13 the two spectra are presented, the one triggered with the OT in black solid line and the one triggered with the Derivative Trigger in red dashed line, for channel 20 using background runs from dataset 2097. OT spectrum goes down to smaller energies, with respect Derivative Trigger. As it can be seen, the number of events dramatically increases going toward 0 keV. This large number of counts has to be ascribed to noise events and not to wrong triggers, as for example triggered side lobes, generated from the new implementation of the OT. This rise in the spectrum can be seen as the right tail of a very high Gaussian distribution of noise events centered at 0 keV.

To proof that it is not the new trigger the cause of this “peak”, it is possible to compare its old and new versions on the CCVR2 (see the previous section). In fig.4.14 it is presented this comparison: the two spectra are totally compatible till the smallest value considered (3 keV). In fig.4.13 there are no cuts applied to the data, to magnify the difference between the two triggers, while in fig.4.14 some cuts are applied to select only pulses of physical events.

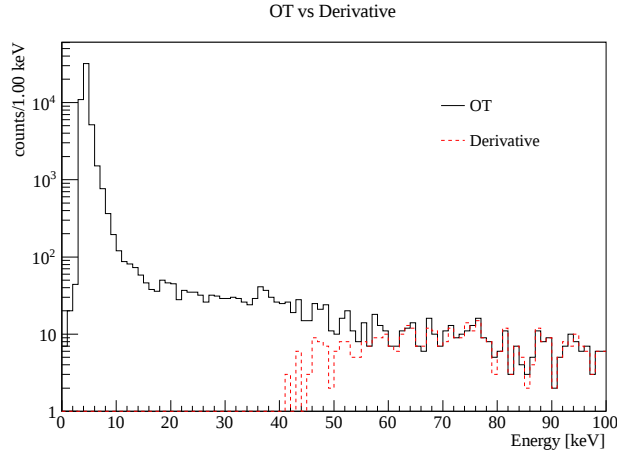


Figure 4.13: Comparison of the OT and Derivative trigger on background runs from dataset 2097 for channel 20. OT spectrum goes to smaller energies and presents a very high peak in the lowest part. This peak can be interpreted as the right tail of noise events whose distribution is a Gaussian centered at 0 keV. No quality cuts are applied to the data in these spectra.

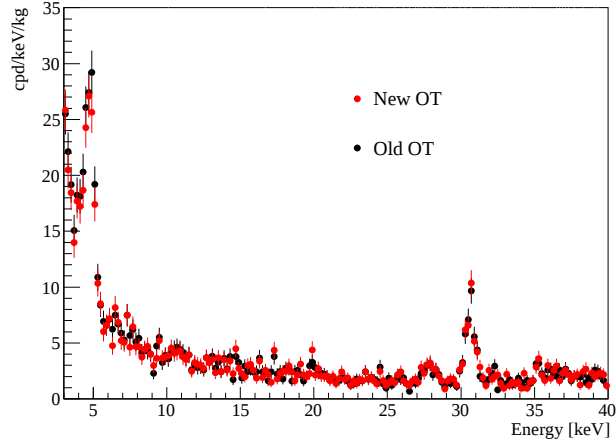


Figure 4.14: Old and new OT versions applied to CCVR2. The two spectra are the result of the sum over 3 channels. Going towards low energies the two spectra are compatible, meaning that the new version of the trigger does not introduces fake events, like triggered side lobes. Quality cuts are applied to the data, fundamentally to rejects spikes (see sec.5.2.1.1).

Chapter 5

Low energy analysis

5.1 Introduction

To set limits on DM, once data are triggered with the OT, it is necessary to generate the low energy spectra of CUORE-0 channels. These spectra are produced using the so-called *first-level analysis*. During this analysis, triggered data are energy-calibrated and many other quantities are evaluated for each pulse.

Particular attention must be put into the calibration quality control, which for low energy region is harder to check than for the standard one, given the absence of a suitable energy peak in the calibration sources used in CUORE-0. Consequently a dedicated approach has been developed to overcome this problem and verify the correctness of the calibration function.

This chapter presents all the steps to be followed in the standard analysis; subsequently the method for assessing the quality of calibrated data is described.

5.2 First-level analysis

After detector signals have been digitized and triggered, it is possible to start with the first-level analysis. With this procedure an energy value is associated to each pulse, more precisely to its amplitude. In addition several environmental informations (like event time, channel number, detector floor, etc.) and pulse shape parameters are stored. To reach this goal, four steps are needed during this offline analysis:

1. *Optimum Filter*, to correctly evaluate the pulse amplitude;
2. *stabilization*, to eliminate the signal dependence on the temperature variation of the thermal bath;
3. *calibration*, to give an energy value to the pulse;
4. *coincidences*, to calculate time coincidences between events.

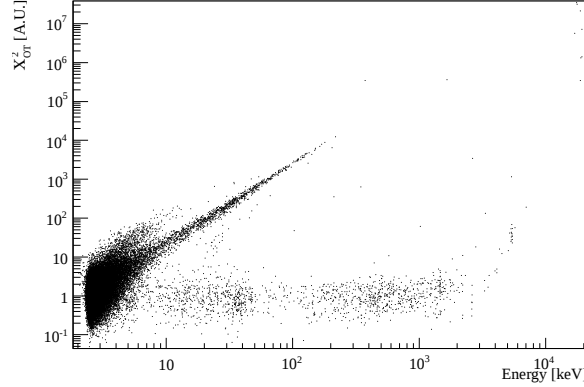


Figure 5.1: χ^2_{OT} versus energy (see sec.5.2.3 for energy calibration) for channel 46 in dataset 2088. Looking at the corresponding pulses, bad ones are characterized by higher values of χ^2_{OT} starting from low energies. Augmenting energy, also good pulses start to rise their χ^2_{OT} value, since their shape depends on energy itself.

5.2.1 Optimum Filter

This algorithm has been deeply discussed in sec.4.2. The reason of its implementation is that a simple maximum-minus-minimum algorithm, applied to the acquired window, would be spoiled by the stochastic noise of the detector. Since OF maximizes the SNR, it optimizes the signal resolution. Hence the filtered pulse height is taken as the signal amplitude. The OT filtering is repeated because those windows are used only to trigger and are not saved.

5.2.1.1 Shape parameter

As previously stated, the OF is sensitive to pulses having the same shape of the average signal. When a pulse with different shape occurs, its filtered amplitude is suppressed and the filtered shape also is different from expectation. To suppress fake signals a pulse shape indicator was implemented in the analysis code.

The algorithm is relatively simple. A triggered pulse is fitted using a cubic spline of the filtered average pulse, and the χ^2/ndf of the fit is used as shape indicator. The cubic spline is needed to have a continuous function, and to fit fractional time delays. The fitted parameters are the amplitude and the position of the pulse, while the baseline is fixed at zero. Since the OF is already a fit of the data samples, this fit only serves to remove the digitization effects and to estimate the χ^2 . Before fitting, the maxima of the fit function and of the triggered pulse are aligned. The pulse position is then varied in the range $[-1, 1]$ samples, that is the maximum possible shift due to digitization. The amplitude is varied in the range $[A, A/(1 - \epsilon)]$, where A is the amplitude

of the filtered signal and ϵ is the maximum allowed suppression in amplitude due to the digitization. This parameter is estimated from the filtered average pulse, computing the amplitude difference between the maximum (which has unitary amplitude) and the amplitude of the point right after. The fit range L corresponds to four filtered average pulse widths.

Finally, the shape indicator is computed as:

$$\chi_{OT}^2 = \sum_{i=0}^{L-1} \frac{(\tilde{y}_i - f_i)^2}{\sigma_L^2(L-2)} \quad (5.1)$$

where $\tilde{y}$ is the filtered signal, f is the estimated fit function, and σ_L is the amount of noise expected in a window of length L . The error of each point, in fact, is not the average error of the entire filtered window in eq.(4.11), but it is lower since low frequencies are not seen in a smaller window:

$$\sigma_L^2 = \sum_{k=M/L}^{M-M/L} h^2 \frac{|s(\omega)|^2}{N(\omega)}.$$

It must be noticed that, even if eq.(5.1) has the form of a χ^2 it does not follows a true χ^2 distribution. The expected value is still 1, but the variance is not $2/(L-2)$ since the errors are correlated at the filter output. An example of its distribution as function of the energy (see sec.5.2.3 for energy calibration) is given in fig.5.1 for channel 46 in dataset 2088, where good and bad pulses are easily identifiable, the latter having higher χ_{OT}^2 already at low energy. The reason why also good pulses start to have a large value of χ_{OT}^2 at some energy is due to the fact that the pulse shape depends on energy.

The trigger and the pulse shape algorithms take advantage of the informations that can be extracted from the OF theory. All the parameters are fixed and automatically calculated at the DAQ start. Actually the χ_{OT}^2 turns out to be the most powerful parameter to discriminate between good physical events and other kinds of events, like spikes, tower vibrations or sharp baseline jumps, e.g. in fig.5.2.

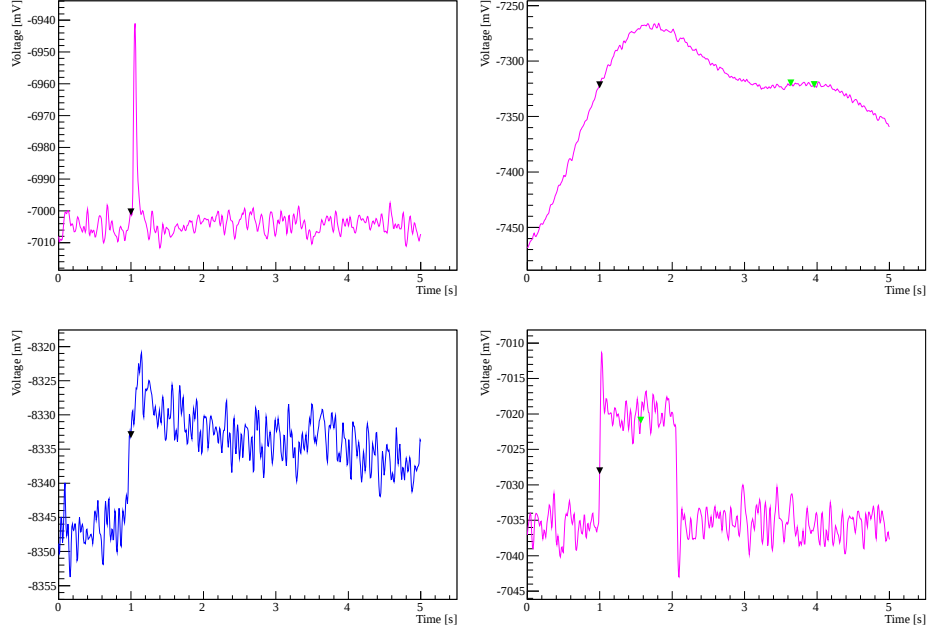


Figure 5.2: Examples of bad pulses. Top left is a spike ($\chi_{OT}^2 = 79.5106$), generated by electronics or by a radioactive decay on the thermistor. Top right is the “pulse” produced by a tower vibration ($\chi_{OT}^2 = 687.199$), generally due to vibration induced by the cryostat or to the water pump located in the CUORE-0 hut. Bottom left is a sudden baseline jump ($\chi_{OT}^2 = 5.54894$) and bottom right some electronic noise ($\chi_{OT}^2 = 8.29397$). All these kind of events is easily rejected using χ_{OT}^2 .

5.2.2 Stabilization

Signal amplitude is highly dependent on the bolometer temperature. Consequently two isoenergetic events may have different pulse amplitude. This would dramatically worsen the detector energy resolution.

To reduce this effect a pulser is used, as mentioned in sec.3.3.2. The pulser is a resistor that, due to the Joule effect, heats up when a current runs through it. In this way it releases some energy (always the same quantity) in the bolometer, simulating an event. Anyway a heater event is distinguishable from a real event (see sec.5.2.1.1). Exploiting this knowledge it is possible to stabilize signals, imposing that every pulser event has the same amplitude. This procedure provides a function that is used to correct each pulse amplitude.

The heater signal amplitude $a_h(b)$ (function of the baseline b , directly connected to the temperature) and the energy release E_h , are related by:

$$a_h(b) = G(b)E_h$$

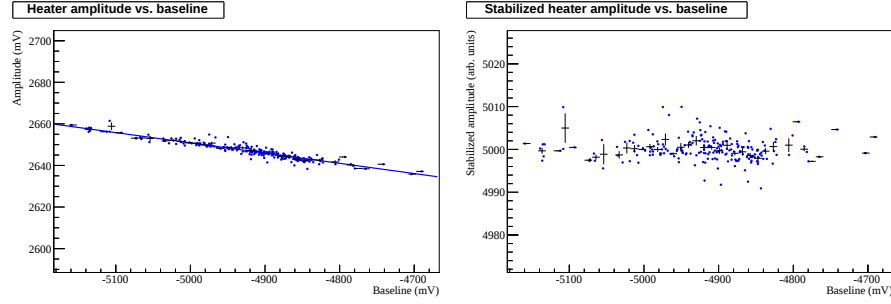


Figure 5.3: Pulser amplitude as a function of the detector baseline before (left) and after (right) stabilization. The blue line on the left is the result of a linear fit. Stabilized pulser amplitude is set to an arbitrary value of 5000 (right).

with $G(b)$ the gain of the bolometer, namely the signal amplification. Therefore for an event with amplitude a that released an energy E

$$a = G(b)E = \frac{a_h(b)}{E_h} E.$$

Starting from this, it is possible to observe that a/a_h is a constant function of the baseline and is proportional to the energy. At the end the stabilized amplitude is obtained as

$$a_s = \frac{a}{a_h} \cdot 5000$$

where 5000 is an arbitrary scale factor. It should be noticed that it is implicitly assumed that this correction factor is not dependent on the energy deposited in the bolometer.

In fig.5.3 the pulser signal amplitude is shown as a function of the baseline before (left) and after (right) the stabilization. On the left also the fitting line is shown; in this case it is a straight line, but the analysis software can account for up to four different regions in which subdivide the scatter plot and try to stabilize the measurement.

5.2.3 Calibration

During the calibration process an energy value is assigned to the pulse amplitude. This is performed using known peaks in the energy spectrum of the bolometer. Since the goal of CUORE-0 is the lowest contamination possible, there are no internal lines intense enough to calibrate the detector in a reasonable time. Consequently a ^{232}Th radioactive source is introduced between the outer vacuum chamber and the external lead shielding (sec.3.3.2). Tab.5.1 lists all the peaks employed for the spectrum calibration. The presence of a second source means that the primary and the secondary lines are summed in a single peak in the spectrum.

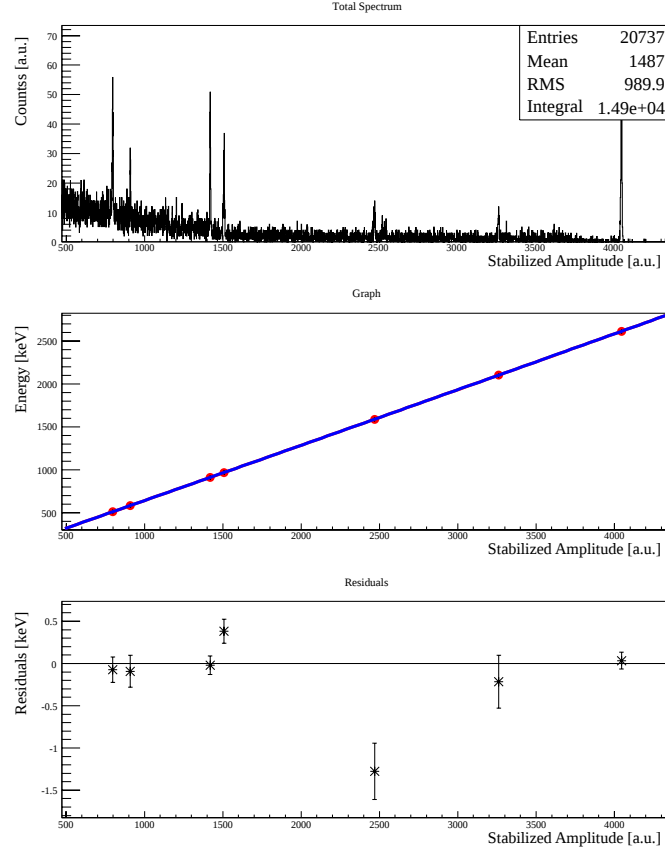


Figure 5.4: A CUORE-0 calibration function example. All seven peaks (see tab.5.1) are used to calibrate the energy spectrum. In every graph on the x-axis there is the stabilized amplitude. In the top panel there is the spectrum, in the middle the fitting function and in the bottom are shown residuals at the nominal energy of the peaks. Although a second degree function with zero intercept is employed, the calibration function is practically linear.

Source	Energy [keV]	2^{nd} source	2^{nd} energy [keV]	Amplitude ratio
e^+e^-	511.0			
^{208}Tl	583.191			
^{228}Ac	911.204			
^{228}Ac	968.971	^{228}Ac	964.766	0.240
^{228}Ac	1588.9	^{208}Tl double esc.	1592.533	no ratio
^{208}Tl single esc.	2103.533			
^{208}Tl	2614.533			

Table 5.1: Calibration peaks from a ^{232}Th source. If present, 2^{nd} source means that there are two lines that sum in a single peak in the energy spectrum. The amplitude ratio is defined as the branching ratio of the second decay divided by the branching ratio of the first decay within a peak; no ratio means that the sources are not correlated. Single and double escape are the energy of the ^{208}Tl peak (2614.533 keV) with a single or a double photon escape (of 511.0 keV each) from the crystal, respectively.

The fitting function is a second degree polynomial with zero intercept, since it is assumed that for a zero deposit of energy there is a zero amplitude pulse¹. Previously a third degree function with zero intercept was used to calibrate the spectra, but the calibration formula was changed after the demonstration that the second degree polynomial resolves better the peaks in the α region (above the ^{208}Tl line), leaving unchanged the ones in the γ region (from 0 to the ^{208}Tl peak). An example of CUORE-0 calibration function is shown in fig.5.4.

5.2.4 Coincidences

Time coincidences are needed to identify signals generated by events that deposit energy in multiple crystals. The number resulting from coincidence evaluation is called multiplicity and is defined as the number of channels that record a signal within a defined time window of each other. In this analysis the interval duration is 100 ms. This window is said to be running, meaning that the time counter is reset every time that a signal is triggered, as long as the time elapsed between two consecutive events is smaller than the window length. Hence, if some particle, vibration or other perturbation crosses the tower, inducing signals on various bolometers, all these registered events are correlated by the multiplicity. If two events (and no others) are in time coincidence they have a and are called M2 events.

Before calculating the multiplicity of an event, an energy and a χ^2_{OT} cut (only for energies smaller than 1100 keV) are implemented:

¹When the constant term is left free to vary, it results compatible with zero.

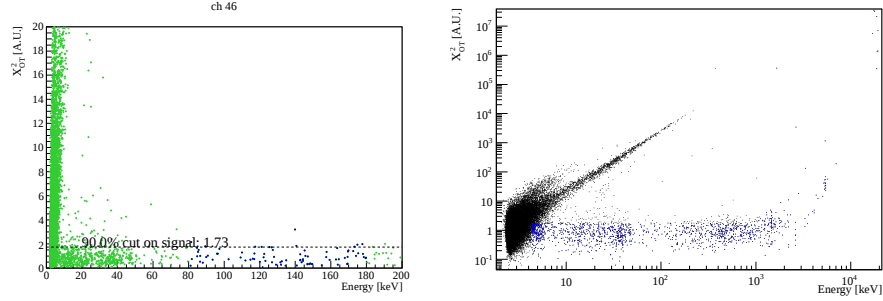


Figure 5.5: χ_{OT}^2 versus energy for channel 46 in dataset 2088. Left: in blue are highlighted events in the selection $80 \div 180$ keV and $\chi_{OT}^2 < 10$ used to calculate $\chi_{OT-90\%}^2$. Right: in blue are indicated the points considered for the multiplicity calculation. Only high quality/physically interesting events are included.

$$\left\{ \begin{array}{ll} E < OT_{99\%} & \Rightarrow \text{discarded} \\ OT_{99\%} \leq E \leq 1100 \text{ keV} & \Rightarrow \text{kept if } \chi_{OT}^2 < \chi_{OT-90\%}^2 \\ E > 1100 \text{ keV} & \Rightarrow \text{kept} \end{array} \right.$$

where E is the event energy, $OT_{99\%}$ is the energy at which the OT reaches the 99% trigger efficiency (different for every channel and dataset) and $\chi_{OT-90\%}^2$ is the χ_{OT}^2 value corresponding to the 90% efficiency cut on signal events (channel and dataset dependent). The 99% trigger efficiency is calculated via the error function (see sec.4.4). The $\chi_{OT-90\%}^2$ is obtained from the χ_{OT}^2 distribution of events in the $80 \div 180$ keV interval with $\chi_{OT}^2 < 10$, being that only signal pulses are present in this region, as evident looking at fig.5.1 left. The energy cut is to avoid undesired coincidences with noise events at low energy, while the χ_{OT}^2 cut in the $OT_{99\%} \div 1100$ keV interval is to prevent coincidences with other non physical pulses, that can extend up to the MeV region.

Hence an event of defined multiplicity (namely multiplicity ≥ 1) belong to high quality data. An example of the application of these cuts is given in fig.5.5, which is the same of fig.5.1 right, with selected points highlighted in blue: almost all the noise and non physical events are excluded from the multiplicity calculation. Hereafter referring to multiplicity, this notation will be used: M1 for multiplicity = 1, M2 for multiplicity = 2 and so on.

5.3 Calibration check

Dealing with energy spectra it is fundamental to check the calibration quality. In the MeV region this is simple, since it is automatically done when the radioactive ^{232}Th source is used: residuals at nominal peak energies are measured during the calibration, as explained in sec.5.2.3. Instead, at low energy, the calibration

Origin	Energy [keV]	Intensity per 100 vacancies in the K-shell [%]
K _{a3}	26.875	0.00202
K _{a2}	27.202	25.3
K _{a1}	27.472	47.1
K _{b3}	30.944	4.25
K _{b1}	30.995	8.19
K _{b5}	31.237	0.075
K _{b2}	31.704	2.37
K _{b4}	31.774	0.363

Table 5.2: Energies and intensity of K-lines originated from Te around 27 keV and 31 keV. Numbers from [78].

quality is harder to verify. This is due to the fact that no peaks are clearly visible in the very low energy range.

A possible way is to look at the spectrum of M2 events. This is due to the possibility to find a peak around 27 keV, originated by three different X-rays from Te, as indicated in tab.5.2. These lines are produced when the Te in a crystal hit by a particle is excited and releases one of these X-rays, which is then detected by an adjacent crystal. In background runs the statistics is too low to see anything, while in calibration runs this behavior is enhanced by the presence of the source. In particular right below most intense peaks there should be a smaller peak, with an energy equal to the energy of the main peak minus the X-rays average energy. This secondary peak should be more visible below the 2614.5 keV line, due to this peak higher rate and to the smaller background with respect the other ones.

Unfortunately, even for the dataset with the longest calibration (9.26 d for dataset 2088), there is not an evident peak in the single channel spectrum arising from the X-escape, neither around 27 keV, nor below the 2614.5 keV. Only grouping almost all channels of this calibration it is possible to see the X-ray peak in the M2 spectrum, as shown in fig.5.6. Here, additionally, a smaller peak is visible at about 31 keV, also produced by the sum of various Te lines that have lower intensities with respect to the 27 keV ones (tab.5.2). The 8 channels with the most and the worst resolutions have been discarded to produce this spectrum, to avoid that these pollute the peak region due to their high energy threshold.

Given the situation, the unique way is to put all the reprocessed calibration runs, from different datasets, together for a single channel. A simple sum of datasets with no further assumptions is not justified, as calibration coefficients are evaluated on a dataset basis. To overcome this problem and check the inter-dataset calibration, it is possible to use the pulser. As explained in sec.4.4, a n-pulsers measurement is performed in each dataset, thus selecting always the same pulser configuration (namely the dissipated power in the bolometer) it is possible to verify if its corresponding energy remains unchanged going through

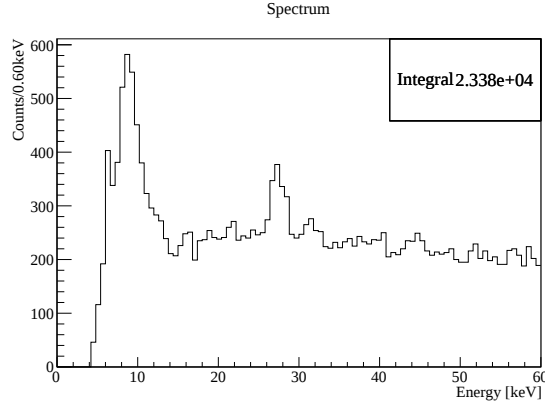


Figure 5.6: Two peaks are evident in the M2 spectrum of calibration runs of dataset 2088, at 27 keV and 31 keV. Both produced by Te K-shell X-rays, as indicated in tab.5.2. To obtain a good energy spectrum the worst 8 channels (noisy or with bad energy resolution) have been discarded.

Channel	Datasets
5	2079, 2100, 2139
15	2124, 2130, 3139
22	2124
27	2079, 2097, 2124
29	2130
34	2130
37	2130
43	079, 2085

Table 5.3: List of datasets to be discarded for each channel due to a non stable calibration, probed with the pulser.

all the datasets. Pulser energies are selected to be in the region of interest DM and vary from ≈ 10 to ≈ 30 keV, depending on the channel. For example, fig.5.7 shows the outcome for channel 52.

Once heater peaks have been fitted, results can be put together to select good datasets and discard the others. In fig.5.8 is shown the outcome for channel 52. A dataset is maintained if the corresponding value is no more than $\sigma_{\text{dataset}} + 1$ keV from the mean, where σ_{dataset} is the error associated to the measured value. To make it easier to see in fig.5.8 the ± 1 keV region is highlighted with a grey band around the mean. Tab.5.3 is the list of discarded channel/dataset pairs.

With the list of compatible datasets for each channel, it is now possible to group them and reach the highest calibration statistics possible. The fit on the 27 keV peak is performed using a fixed resolution gaussian plus a flat

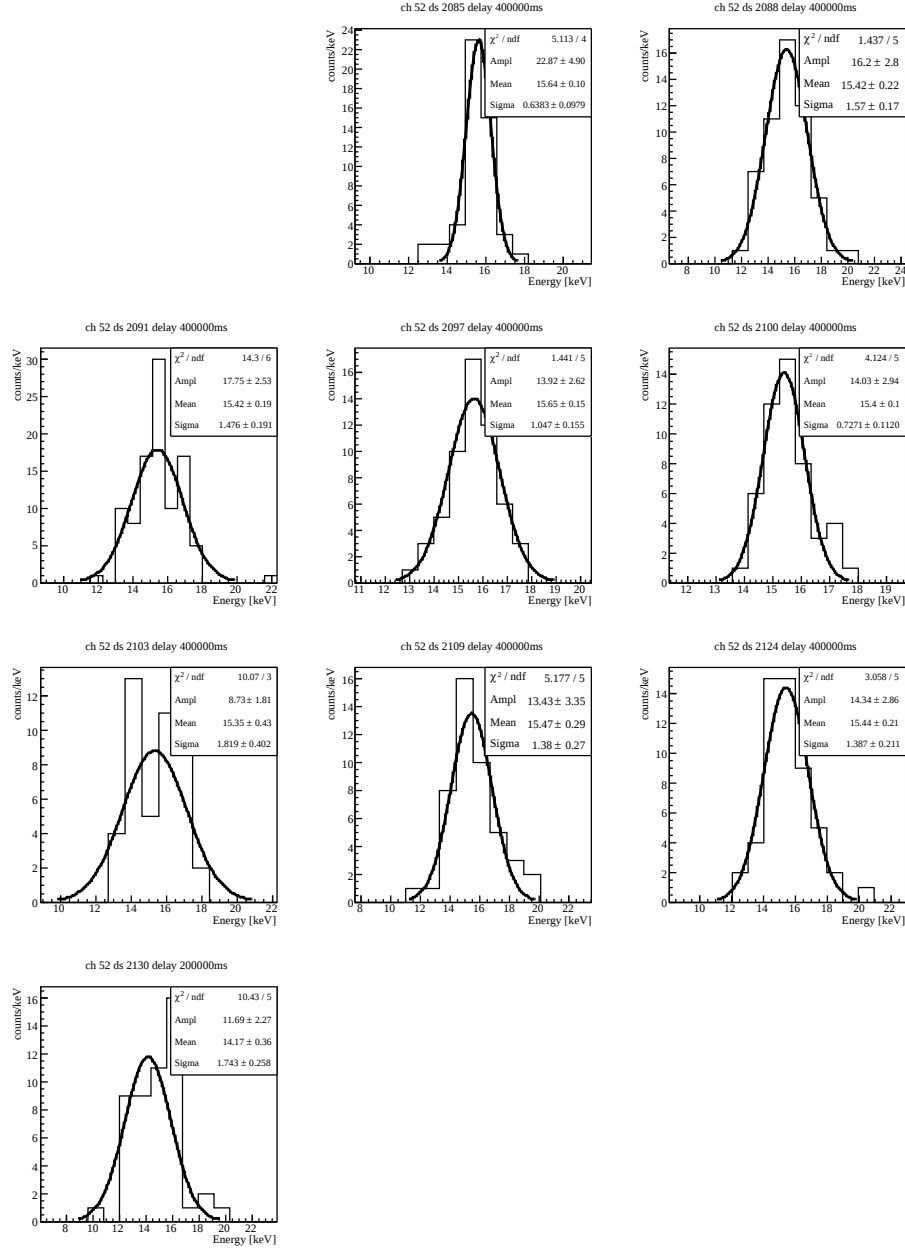


Figure 5.7: Fits on pulsers for channel 52, one per dataset. Datasets 2079 and 2139 (the first and the last ones) are absent because these whole datasets are marked as bad interval for this channel. Going across all the datasets always the same pulser is selected, so that low energy calibration stability can be checked.

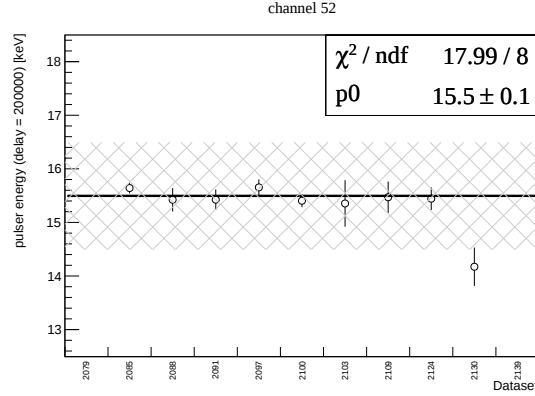


Figure 5.8: Pulser stability of channel 52. Each point represents a dataset, while the gray band corresponds to the mean energy ± 1 keV. The dataset is considered good if the distance between its point and the mean is smaller than $\sigma_{\text{dataset}} + 1$ keV, where σ_{dataset} is the error for that dataset: in this case dataset 2130 is maintained, since its point error and the gray band are in “touch”. Datasets 2079 and 2139 (the first and the last ones) are absent because these whole datasets are marked as bad interval (see sec.3.3.3) for this channel.

background. The fixed sigma is required to increase the fit quality and the number of positive results, reducing the free parameters. Its value is channel dependent and is assumed to be equal to the baseline resolution as comes from all the selected calibration runs. The bolometer baseline is attained by means of a dedicated trigger, that takes the name of Random Trigger, that every 300s takes the detector data flow content and stores the measured sample. Consequently the acquired points distributions are gaussians with a resolution given by baseline RMS.

Four different sets of data are taken into account for the 27 keV peak fit:

- M1 events,
- M2 events with total energy larger than 20 keV,
- M2 events with total energy larger than 100 keV,
- M2 events with total energy larger than 500 keV;

where total energy is the sum of the energies of the two events that compose the pair. The higher the total energy, the lower the background, and the lower the statistics. To give an example, in fig.5.9 are the four spectra for channel 32. In this case there is a visible peak only in the M2 spectrum with total energy higher than 500 keV. In total, 22 channels show a well fitted peak in at least one spectrum. The complete list is in tab.5.4. Consequently only these channels can be used to produce low-energy spectra and thus for DM study.

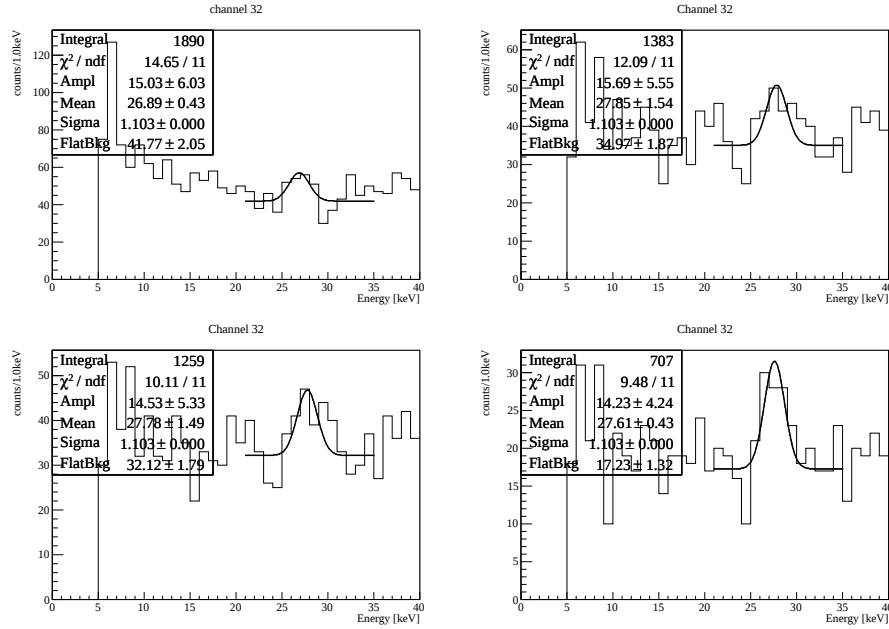


Figure 5.9: Fixed sigma gaussian plus flat background fits to the 27 keV peak for channel 32 on four different kind of spectra: M1 (top left), M2 with total energy larger than 20 keV (top right), 100 keV (bottom left) and 500 keV (bottom right). Total energy is the sum of the energies of the events that compose the pair (hence the single event energy, the one plotted, can be arbitrarily small). The peak is unambiguously identifiable only in the fourth case.

Comparing tab.5.3 and tab.5.4 it can be noticed that none of the good channels has a dataset to be excluded because of calibration instability.

Finally, to check the overall calibration of the detector, a fit on the spectrum obtained by grouping these 22 channels is performed. The fit is implemented on the 27 keV and on the 31 keV peaks using a flat background and two gaussians with a common sigma. The result is presented in fig.5.10. Making a weighted mean of the lines of tab.5.2 the expected values for the peaks are 27.38 keV and 31.11 keV, while the measured ones are 27.50 ± 0.06 keV 31.47 ± 0.16 keV, respectively. Both are compatible within 2σ with the real values, and lead to a weighted mean calibration uncertainty of 0.15 keV at 28.03 keV.

Spectrum kind	Channels
M1	19, 45 (2)
M2 $E_{\text{TOT}} > 20$ keV	2, 3, 6, 7, 9, 12, 17, 18, 19, 20, 21, 24, 25, 26, 31, 36, 41, 44, 46 (19)
M2 $E_{\text{TOT}} > 100$ keV	2, 3, 6, 7, 9, 12, 17, 18, 19, 20, 21, 24, 25, 26, 31, 36, 41, 44, 46 (19)
M2 $E_{\text{TOT}} > 500$ keV	2, 3, 4, 6, 9, 12, 14, 17, 18, 19, 20, 21, 24, 25, 26, 31, 32, 41, 46 (19)
All kind	2, 3, 4, 6, 7, 9, 12, 14, 17, 18, 19, 20, 21, 24, 25, 26, 31, 36, 41, 44, 46 (22)

Table 5.4: List of channels that show a well fitted 27 keV peak, divided into the four kinds of spectra. The total number of channels is indicated in parentheses. E_{TOT} indicates the total energy of the couple of events.

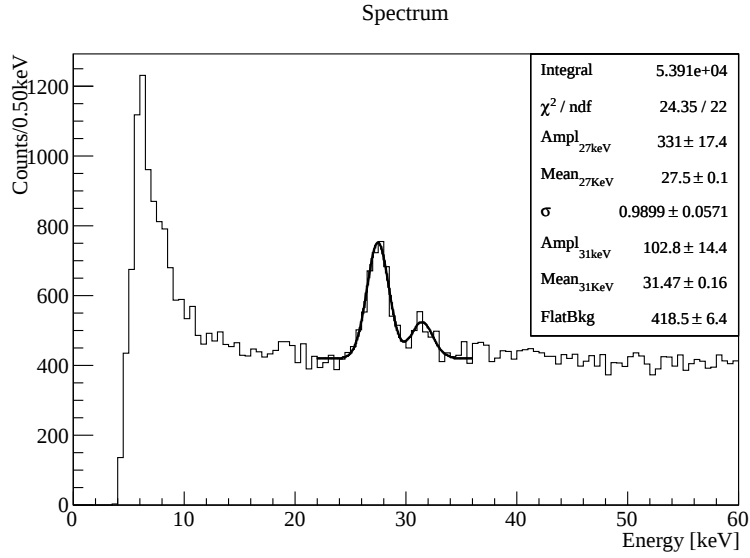


Figure 5.10: Global fit to the 27.38 keV and 31.11 keV peaks. All 22 channels indicated in tab.5.4 are used. The overall calibration uncertainty is 0.15 keV at 28.03 keV.

Chapter 6

Low energy spectrum and modulation analysis

6.1 Introduction

Once energy calibration has been checked in the keV region, it is possible to apply ulterior runs selection before to draw the detector low energy spectrum, in order to work with data of the highest quality possible. This selection is fundamentally focussed in lowering the achievable spectrum energy threshold and counting rate. Then, starting from this spectrum, one can choose which approach to follow for the DM analysis.

In this last chapter are presented the the low energy spectrum of CUORE-0, the analysis technique and the obtained results to study DM.

6.2 Runs selection

Before proceed with the low energy spectrum production, some additional data screening must be added in order to improve the data quality. One cut has been already describe in sec.5.3: the list of channel/dataset pairs to exclude due to calibration instability (summarized in tab.5.3). Two further selections are applied: one is to remove five runs where the events counting rate is extremely high and the other is to maintain only runs with low noise and hence a good energy resolution.

6.2.1 High counting rate runs

For not yet completely understood reasons, there are five runs, the final ones of dataset 2109, where the counting rate of low energy events explodes to values much higher than the rest of the dataset and of CUORE-0 in general. In fig.6.1 is presented the counting rate of channel 19 as a function of time for M1 events

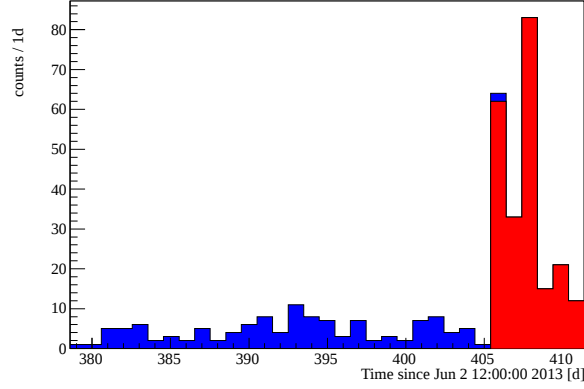


Figure 6.1: Channel 19 time displacement of events from $10 \div 15$ keV range in dataset 2109. The bin width is 1 d. In red are highlighted the five runs with a very high event rate.

in the $10 \div 15$ keV range. It is evident that during the last days of the dataset something happened in such a way that this runs (indicated in red) account for a large part of the total number of events (up to the 65%). This effect is more evident on the top of the tower than on the bottom, leading to the idea of a mechanical source, like cryostat vibrations.

A useful tool to try to understand the origin of this phenomenon is the NPS: if the source is mechanical or electronic, one or more peaks should be visible at some characteristic frequency. Comparing NPS of these runs with respect other runs for various channels, no notable differences are visible (see fig.6.2 as example), leaving unsolved the problem.

Independently from the reasons of these counts, it is undeniable that such an high rate would spoil both the low energy spectrum and the DM study. Consequently it has been chosen to exclude these runs from the subsequent studies.

6.2.2 Low noise runs

Aiming to the lowest energy threshold possible, the exclusion of noisy runs is a fundamental step. The simplest way to perform this is to discard runs with a large baseline resolution. The baseline resolution of each run is evaluated as the RMS of the points sampled using the Random Trigger, already mentioned in sec.5.3. The value to apply the cut is $\text{median} + 2 \text{RMS}$, where both are referring to the distribution of the run resolutions, in particular RMS is referring to the RMS of the RMSs (namely the resolutions) distribution. The 2RMS cut is effective, but do not remove too much statistics. From this calculations are excluded the five high counting rate runs and the runs belonging to a dataset marked as bad from the pulser stability study, that are channel dependent. An

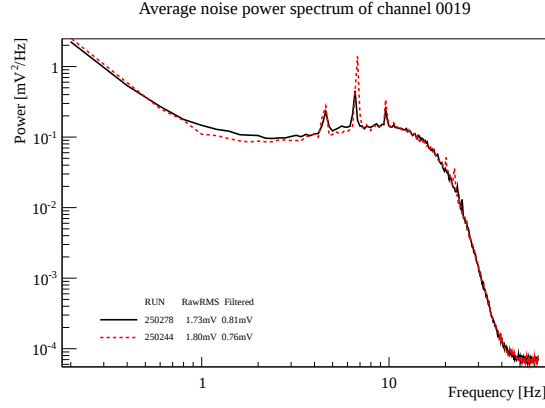


Figure 6.2: NPS comparison for two runs of dataset 2109 for channel 19. One of the two belong to the five runs with an high counting rate (250278). There are no evident differences, like a new peak at some frequency, as expected if the source of these events is mechanical or electronic.

example of this is given in fig.6.3 for channel 17. Here each point represents a run resolution, expressed as a function of time for a more easy understanding of the detector behavior during data taking. The time scale is in days since June 2nd 2013 in vision of the future DM analysis (see sec.6.4). Here the dashed line represents the applied cut, hence runs corresponding to points over it are discarded.

6.3 Low energy spectrum

Now that the whole data selection has been defined, it can be implemented to draw low energy spectrum of CUORE-0. To these data are applied some cuts to select the desired kind of signal: all the bad intervals are rejected and only M1 events are considered (hence a χ^2_{OT} cut is implicitly implemented, as described in sec.5.2.4). The trigger and cuts efficiencies are evaluated as follows:

- OT: only energies larger than the one at which the trigger reaches the 99% efficiency are considered; hence efficiency is assumed as unitary.
- χ^2_{OT} : in this case it is first decided the efficiency and then the cut value comes consequently. In particular the chosen efficiency is 90% and the corresponding $\chi^2_{OT-90\%}$ is measured for each channel/dataset pair. (a more detailed explanation is in sec.5.2.4).
- M1: by means of the ^{40}K peak at 1460.830 keV, produced by a single γ . It is performed a simultaneous fit of accepted and rejected events after the M1 cut application and the efficiency is evaluated as the ratio between the accepted and the total number of the peak events. Both

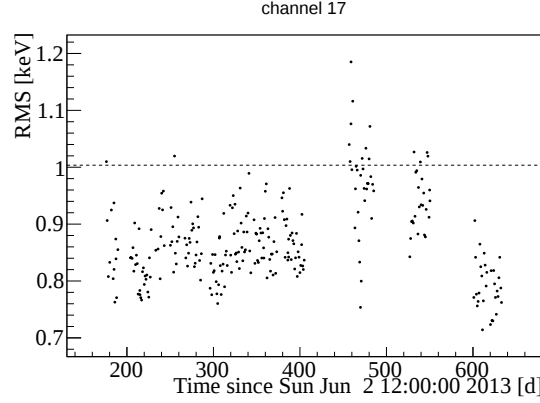


Figure 6.3: Baseline resolution time trend for channel 17. Each point corresponds to a single run, while the dashed line to the median + 2RMS of the distribution along the y-axis. Runs with a resolution below this line are maintained, the others are excluded from the analysis.

populations are shown in fig.6.4. The fit components are a gaussian plus a flat background. To obtain a result as much consistent as possible with the data, only selected channels and runs are used.

- Bad intervals: they are accounted for in the live time calculation.

Individual spectra are presented in fig.6.5 for all the 22 selected channels. As it can be seen all the spectra exhibit a quite homogeneous behavior.

Putting together all these channels one obtains the global spectrum, for a total exposure of $9.25 \text{ kg} \cdot \text{y}$. This is displayed in fig.6.6 top and it can be noticed that, despite the number of counting is low, also if compared to the one in CCVR2 [105], a DM study can be addressed only by means of the annual modulation method. Indeed the DM expected signal is still too small to be directly appreciated as a diffuse increase in the counting rate. Additionally and more in general, unless the detector background is consistently smaller than this, being a featureless spectrum, the one due to DM interactions would be hard to be recognized.

For energies in the range $\approx 30 \div 45 \text{ keV}$ it is evident the presence of two bumps. The nature of these elements is unknown, but they are recognizable also in CCVR2 and characterize the spectrum of each single channel (see fig.6.5). All of this sustains the hypothesis that this is a physical process taking place in the TeO_2 bolometers or in the material surrounding and supporting them. Given the shape and the width probably they are more peaks summed together or some β -decays. In any case a more detailed study will be carried out to understand their origin.

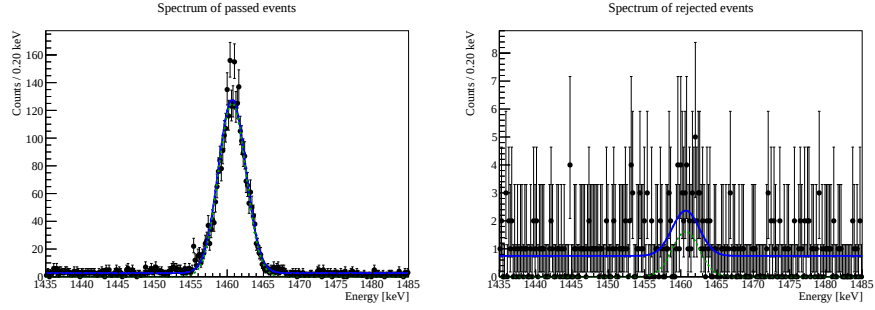


Figure 6.4: Accepted (left) and excluded (right) events for the calculation of M1 cut efficiency from the ^{40}K peak at 1460.830 keV. Accepted are the events that remain after the M1 cut application, while rejected are the ones that are discarded. In blue is indicated the gaussian and flat background sum, in green the peak component only.

6.4 Annual modulation fitting approach and results

DM annual modulation fit is performed on the same data selected for the low energy spectrum, with the additional requirement to take events only from a particular energy range, to probe eventual variations with changing intervals. Three ranges are considered:

- $10 \div 15$ keV,
- $15 \div 20$ keV,
- $20 \div 25$ keV.

To be conservative only channel/dataset pairs with a $\text{OT}_{99\%}$ smaller than the lower bound of the interval are kept. This because a different approach would imply some assumption on the interaction behavior of these particles with the detector. Hence if, for example, a channel/dataset has $\text{OT}_{99\%} = 13$ keV, all the runs of that dataset will not be considered for that channel in the time spectra construction in the $10 \div 15$ keV range, but it will in the other two intervals. This further cut implies that the M1 efficiency is newly evaluated for each considered ensemble, using only channel/dataset that passed the cut.

To correctly draw the annual trend of events, another efficiency must be taken into account: the time bin occupancy. In fact, the detector is not constantly acquiring background runs, hence for each temporal bin there will be a different occupancy efficiency. A proportionality law is applied to correct this effect, e.g. for a bin occupied the 50% of the time, the number of events will be doubled. No modulation corrections are considered because of their small expected amount and more in general because there are no *a priori* informations to evaluate their contribution.

CHAPTER 6. LOW ENERGY SPECTRUM AND MODULATION ANALYSIS

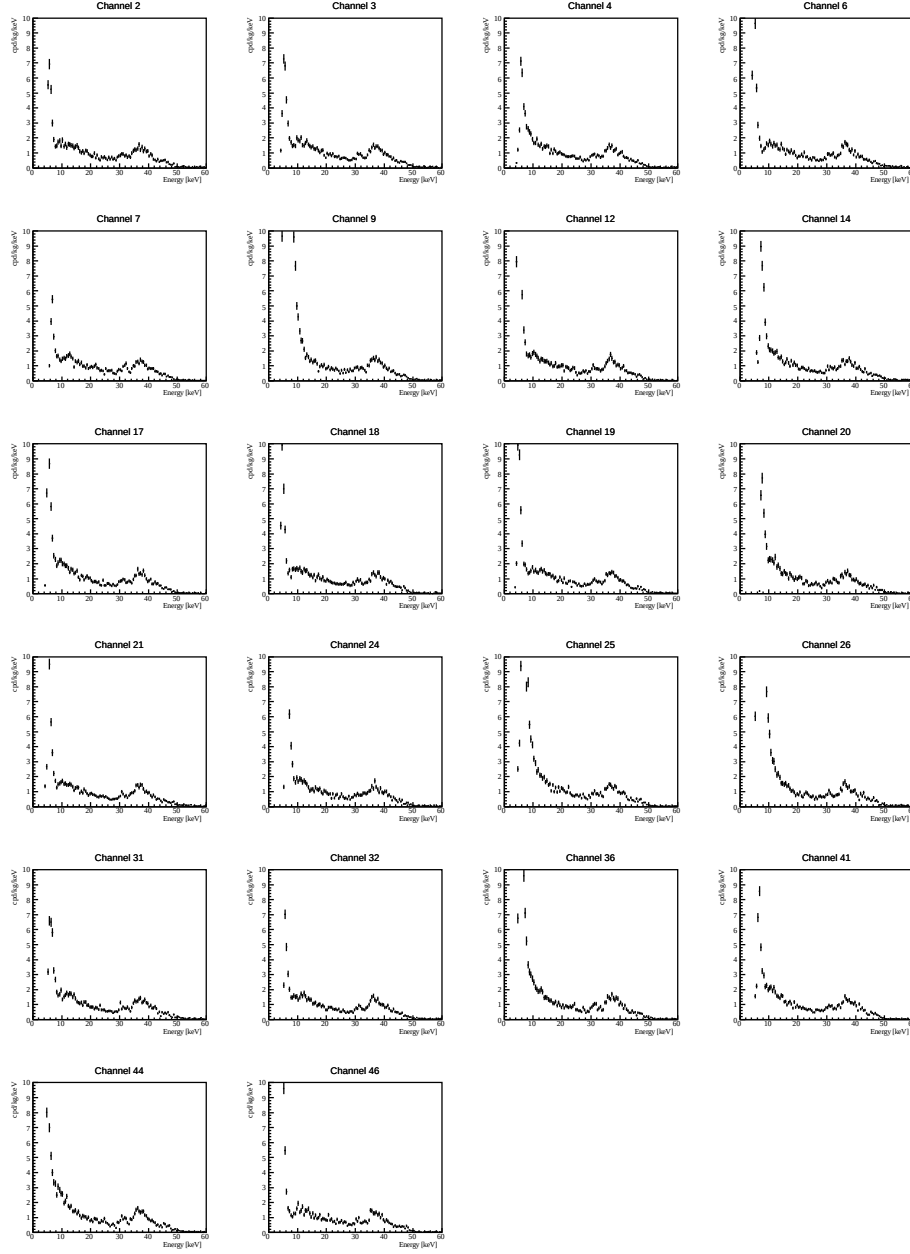


Figure 6.5: Energy spectra of the 22 channels selected for low energy analysis. Each spectrum is in the $0 \div 60$ keV range and binned 0.5 keV, while the y-scale is fixed to $0 \div 10$ cpd/keV/kg. It is evident that the various spectra are consistent among each other.

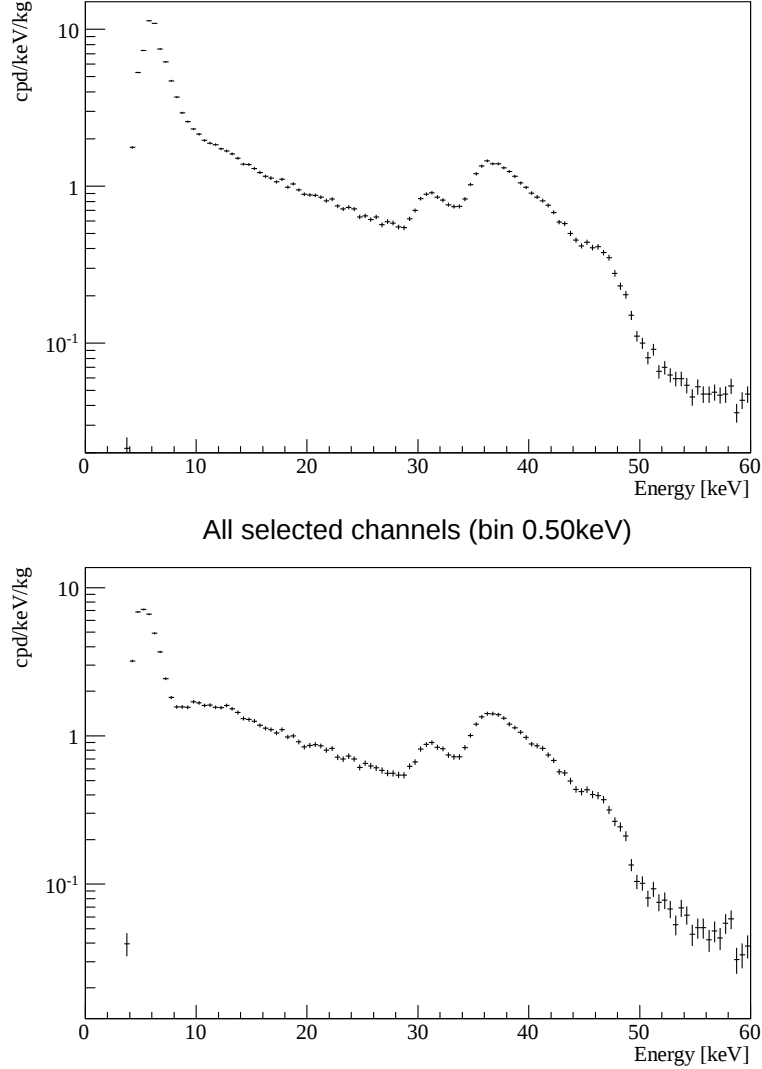


Figure 6.6: Top: global low energy spectrum of CUORE-0 binned at 0.5 keV, produced by the sum of the 22 channels presented in tab.5.4. The total exposure is $9.25 \text{ kg} \cdot \text{y}$. Bottom: global low energy spectrum of CUORE-0 binned at 0.5 keV, produced by the sum of the 12 channels with the best threshold among the ones presented in tab.5.4. The total exposure is $5.00 \text{ kg} \cdot \text{y}$. The logarithmic scale on the y-axis is to enhance the visibility of the two bumps present in the $\approx 30 \div 45 \text{ keV}$ range, just before the drop of the counting rate. The origin of these elements is currently unknown.

As in the energy spectrum case, it is firstly produced the single channel trend and then the global time spectrum. The latter is constructed bin by bin, summing up all the single channel spectra content for that bin (the width is the same), not corrected for the efficiency, that only after is calculated and applied. The fit is performed on the global time spectrum with a flat component plus a cosinusoidal modulation model:

$$B + A \left[1 + \cos \left(\frac{2\pi}{T} (t - t_0) \right) \right]$$

where B is the flat component, that accounts both for the whole non DM signal and for the constant part of DM rate, A is the modulation amplitude, T is the period and t_0 the phase. Two kind of fits are presented: one has T fixed to 1 y and t_0 fixed to June 2nd 2013 (the closest before the considered data), while the other has a period free to vary in the range $0.5 \div 2$ y and a phase free to vary of ± 1 y with respect the fixed t_0 fit date. For the $10 \div 15$ keV interval only the 12 channels whit the lowest threshold are used (5.00 kg · y exposure, energy spectrum in fig.6.6 bottom), whereas the other two exploit all the 22 selected channels (9.25 kg · y exposure). Fig.6.7, 6.8 and 6.9 present the results of these fits. The bin is 30.51 d, since it is automatically calculated trying to satisfy the required width (30 d in this case) and considering the total elapsed time, given by first run start and the last run stop.

The fixed parameters fit has always a modulation amplitude largely compatible with 0, differently from the free parameters one, that has a non null signal, varying from 0.11 cpd/keV/kg in the $10 \div 15$ keV range to 0.024 cpd/keV/kg in the $20 \div 25$ keV range, with a significance varying from 5 to 2 sigmas, respectively. The measured phase shift is always compatible with a phase inversion within 1 sigma. The modulation period is compatible with 365 d within 1 sigma in the $15 \div 20$ keV and $20 \div 25$ keV cases, while for the $10 \div 15$ keV range the difference is more than 7 sigmas. Comparing the expected WIMP rates in TeO₂ for different masses and $\sigma_0 = 10^{-41}$ cm² indicated in fig.6.10 with these numbers, it is evident that they are a factor ≈ 10 smaller than the measured ones.

In conclusion, although a non null modulation amplitude has been measured, given the small exposure, the large errors and the reduced number of annual cycles, there are no stringent evidences to claim for a DM signal detection. The CUORE experiment, with its higher mass and with a larger number of annual cycles, will be able to dwindle errors and to verify if effectively there is a signal modulation repeating in time with the expected period.

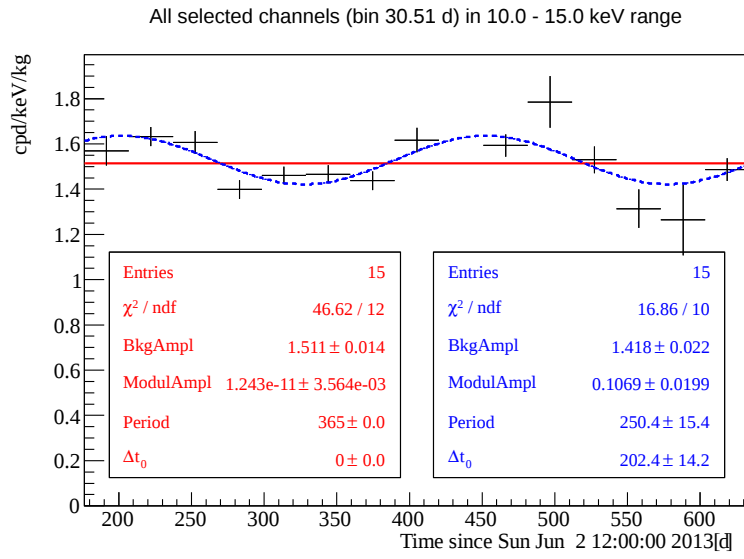


Figure 6.7: Modulation binned fits (bin width of 30.51 d) in the energy range $10 \div 15$ keV. In red continuous line the fixed T and t_0 fit (results on left pad), in blue dashed line the free T and t_0 fit (results on the right pad). The accumulated exposure is $5.00 \text{ kg} \cdot \text{y}$. The fixed phase and period fit is largely compatible with the absence of a DM signal, while the free t_0 one sees an annual modulation of 0.11 cpd/keV/kg amplitude with a phase of 202 d and a period of 250 d.

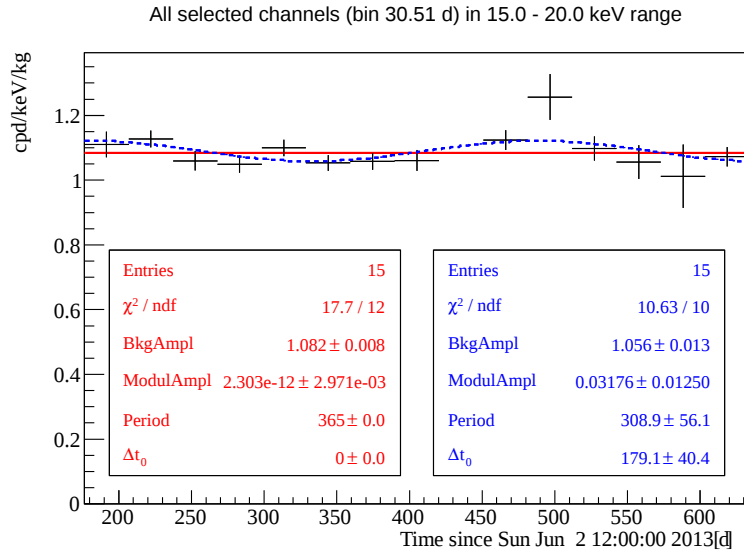


Figure 6.8: Modulation binned fits (bin width of 30.51 d) in the energy range $15 \div 20$ keV. In red continuous line the fixed T and t_0 fit (results on left pad), in blue dashed line the free T and t_0 fit (results on the right pad). The accumulated exposure is $9.25 \text{ kg} \cdot \text{y}$. The fixed phase and period fit is largely compatible with the absence of a DM signal, while the free t_0 one sees an annual modulation of 0.032 cpd/keV/kg amplitude with a phase of 179 d and a period of 309 d.

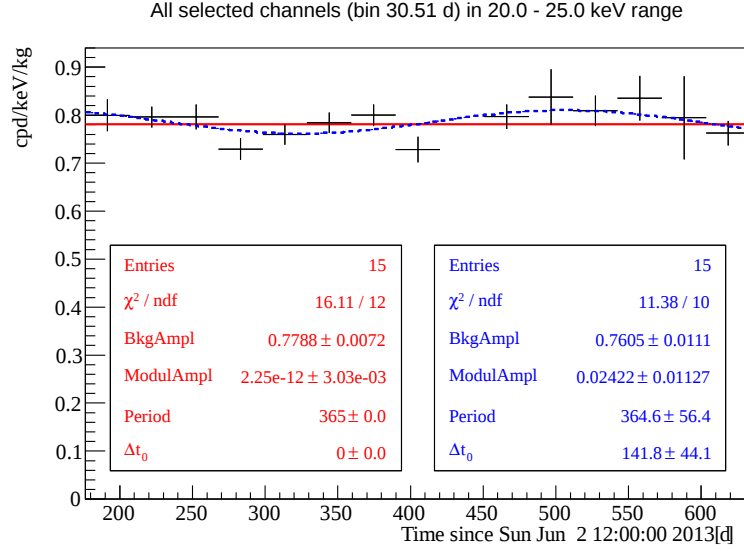


Figure 6.9: Modulation binned fits (bin width of 30.51 d) in the energy range $20 \div 25$ keV. In red continuous line the fixed T and t_0 fit (results on the left pad), in blue dashed line the free T and t_0 fit (results on the right pad). The accumulated exposure is $9.25 \text{ kg} \cdot \text{y}$. The fixed phase and period fit is largely compatible with the absence of a DM signal, while the free t_0 one sees an annual modulation of 0.024 cpd/keV/kg amplitude with a phase of 142 d and a period of 365 d.

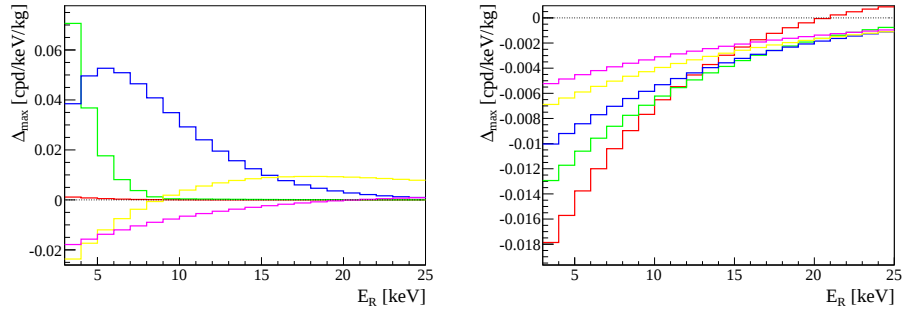


Figure 6.10: Expected maximum minus minimum modulation amplitude in TeO_2 for different WIMP masses (M_χ) as a function of the recoil energy, assuming a cross section of 10^{-41} cm^2 . Left: $M_\chi = 5 \text{ GeV}$ in red, $M_\chi = 10 \text{ GeV}$ in green, $M_\chi = 20 \text{ GeV}$ in blue, $M_\chi = 50 \text{ GeV}$ in yellow and $M_\chi = 100 \text{ GeV}$ in purple. Right: $M_\chi = 100 \text{ GeV}$ in red, $M_\chi = 150 \text{ GeV}$ in green, $M_\chi = 200 \text{ GeV}$ in blue, $M_\chi = 300 \text{ GeV}$ in yellow and $M_\chi = 400 \text{ GeV}$ in purple. Some masses show a modulation phase inversion.

Conclusions

In this Ph. D. work I developed the low energy analysis and I studied the annual modulation with the CUORE-0 detector.

To this end the first step is an improved version of the software-generated low energy trigger. This new version of the trigger shows a 100% detection efficiency plateau for almost all the channels in all the measurement performed, compared to the older implementation that reaches a $\lesssim 90\%$ plateau efficiency. Additionally new tools have been introduced for the data monitoring. In particular now it is possible to foresee the trigger efficiency with *a priori* informations without the need of a dedicated measurement.

Thanks to an energy calibration check, performed at the end of the standard analysis procedure, it resulted that 22 bolometers out of 52 are usable for the low energy studies. At the same time, the overall CUORE-0 calibration uncertainty is evaluated as 0.15 keV at 28.03 keV.

Subsequently, after an accurate event selection, the low energy spectrum of CUORE-0 is produced, for a total exposure of $9.25 \text{ kg} \cdot \text{y}$. The spectrum shows the presence of two bumps between 30 and 45 keV, which origin is currently unknown, probably more peaks summed together or two β -spectra.

Finally, an annual modulation fit has been performed for data arising from three different ranges of the energy spectrum: $10 \div 15 \text{ keV}$, $15 \div 20 \text{ keV}$ and $20 \div 25 \text{ keV}$. Exposure is $5.00 \text{ kg} \cdot \text{y}$ for the lower interval and $9.25 \text{ kg} \cdot \text{y}$ for the remaining two. The fit results show that a modulation signal is present. In the first interval the measured period deviates more than 7 sigmas from 1 y, while in the remaining two cases the signal is compatible within 1 sigma with a period of 1 y and with an inversion of phase with respect June 2nd. Nevertheless, given the small exposure, the large errors and the reduced number of measured annual cycles, there are no clear evidences to claim for a DM signal detection.

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