Characterization of High Quantum Efficiency PMTs for Direct Dark Matter Search with the SABRE experiment

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Anno Accademico 2015-2016
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Introduction

It is well-known that only 5% of our Universe is made of ordinary visible matter, such as electrons, protons and neutrons. About 25%, though, is made of another type of matter, called Dark Matter (DM). This name has been given because its main characteristics are that it does not emit light and that it interacts very weakly with ordinary matter: its presence could be guessed only because of gravitational interaction.

Many observations, from the rotational speed of galaxies, to the cosmological proof given by the Cosmic Microwave Background, lead to the idea of DM being composed by a brand-new massive and neutral particle. Several models have been thought to explain it theoretically and hopefully to detect it. There are two main possible experimental ways when trying to detect DM. The indirect search seeks for DM in its annihilation products, while the direct search looks for collisions of DM particles with ordinary matter, using typical techniques of rare events search physics. This is because the DM cross section is expected to be very low (down to few events/ton/year), so the detection should be done using detectors with exceedingly low intrinsic radioactivity, shielded from cosmic rays and environmental radioactivity in an underground laboratory.

Sodium-iodide with Active-Background REjection (SABRE) is a thallium-doped sodium-iodide experiment designed to search for dark matter through the annual modulation signature. The amplitude of a DM signal in an Earth-based detector is expected to modulate yearly due to the change of the Earth’s speed relative to the galactic halo reference frame. The longstanding result from the DAMA/LIBRA experiment at the LNGS is consistent with this scenario, with a significance of 9.3σ. When interpreted as elastic and spin-independent nuclear scattering of DM particles, the DAMA signal is in tension with null results from other direct search experiments, like XENON, LUX, CDMS and CRESST. Nonetheless, this comparison cannot be regarded as conclusive since it is based on astrophysical, particle and nuclear physics assumptions – i.e. DM energy density, speed distribution, DM nature and nuclear interaction cross section – and a confirmation by an independent NaI experiment is still missing.

The SABRE detector will consist of custom, ultra pure NaI(Tl) crystals, read by low radioactivity, high Quantum Efficiency, low dark noise PMTs, operated in an active liquid scintillator veto and shielded by highly pure water. The experiment will follow a two-phase approach. In the first phase, SABRE will be operated at LNGS as a Proof-of-Principle with the goal of demonstrating the lowering of the background in the region of interest for DM detection at a level that is significantly below the one observed by DAMA/LIBRA. The second phase will consist of two full-scale NaI(Tl) detector arrays located at LNGS
and in the Stawell Underground Physics Laboratory (SUPL), in Australia. The operation of the twin experiments in both the northern and the southern hemisphere will strengthen the reliability of the result against possible seasonal systematic effects.

The low-energy threshold required by SABRE needs an exceptionally good collecting light system in which both the crystals and the PMTs should have the best performance possible. For what concern the crystal, an extremely high radiopurity is foreseen, even at lower levels than the DAMA crystals. About the light collection from the crystal to the PMTs, the goal is to have a direct coupling, without the use of a light guide. This means that the PMTs also have to be highly radiopure and, above all, highly performing. The performance of PMTs depends on some features, such as the Quantum Efficiency (QE), but also on the gain and the dark rate. All these characteristics should be studied in order to choose the optimal PMT on the market, and also in order to try to improve them.

For the SABRE experiment, the Hamamatsu 3” R11065-20 PMTs have been chosen, but they have high dark rate in a room temperature environment. This can be outdone with the production of a new PMT with modified photocathode: the R11065-20 MOD. This prototype is equipped with a superbialkali photocathode which, in principle, allows to obtain a high QE (higher than 35%) with low dark rate in a non cryogenic environment. The main purpose of this work is to make a characterization of three PMTs MOD provided by Hamamatsu, and to compare them with a standard R11065-20. Moreover, it has been possible to test these PMTs also with a NaI(Tl) crystal – not as radiopure as the ones that will be in the experiment – and to calculate the light yield and perform data taking in the underground laboratories where the experiment will be placed.

In Chapter 1, the dark matter problem as it is understood nowadays is presented, including the most relevant candidates, the technique of research and the state-of-art of the direct search.

In Chapter 2 there is a brief introduction related to the DAMA claim that conducts to the description of the SABRE experiment, with the four pillars idea and the Proof-of-Principle aim.

In Chapter 3, after a review of the fundamental characteristics of a PMT and the requirements of SABRE, the operating mode for the characterization of the PMTs under test is described, including the set-up used, the measurements done and the data analysis performed. The coupling of two PMTs and the coincidences and afterglows study are also presented.

Finally, in Chapter 4, there is presented the work done both in the external and in the underground laboratories, with a standard purity crystal added to the set-up and directly coupled with two PMTs MOD. In those same laboratories it was measured the internal background and a first calibration with a radioactive source was made. Further on in the chapter, there are shown the calculation of the light yield of the crystal and PMTs system, the qualitative pulse shape discrimination made on the internal background events and the analysis performed on the $\alpha$s from the uranium and thorium decay chain.
Chapter 1

Dark Matter

Nowadays, it is undeniable that there is presence, in our universe, of an exotic form of matter, non-luminous and non-baryonic. This kind of “dark” matter comprises the 85% of the matter in the universe, and about the 25% of the total energy. However, we can not say more about its properties: the Standard Model of particle physics cannot explain the nature of this dark matter (DM), and this lead us to think that the model should be expanded. So dark matter detection and characterization is one of the main goal of the modern physics.

1.1 Evidences of Dark Matter

All the proofs of the DM existence come from its gravitational interaction with the usual baryonic, luminous matter. The first claim that in the galaxies there should be something invisible but with mass, came from the astronomer Fritz Zwicky in early 1930s. Studying the Coma Cluster, he found out that the velocities of orbiting objects in the cluster were much larger than the ones expected given the total light output. As a matter of fact, the virial theorem states that, for a stable, self-gravitating, spherical distribution of equal mass objects (stars, galaxies, etc), the total kinetic energy of the objects is equal to minus 1/2 times the total gravitational potential energy. In other words, the potential energy must equal the kinetic energy, within a factor of two. In this way, it is possible to estimate the virial mass of the object. Calculating the mass-to-light ratio, Zwicky could understand that about 90% of the mass necessary to account for observed ratio was missing and therefore invisible. He therefore postulated the existence of objects that, gravitationally interacting with the luminous matter, could keep the cluster together, following the laws of Newtonian gravitation.

But it was only in the 1970s that the firsts, convincing proofs of the DM existence were presented.

1.1.1 Rotation curves

One of the strongest evidence for DM on galactic scale comes from the studying of the rotation curves of galaxies, first accurately measured by Vera Rubin.
1.1. Evidences of Dark Matter

Velocity of visible stars or gas on the galactic plane is expected to follow the standard Newtonian dynamics:

\[ v(r) = \sqrt{\frac{GM(r)}{r}} \]

where \( M(r) \) is the mass interior to the orbit radius \( r \). With large radius, one can use the solution for a point of mass \( M \) at the center of the distribution. This leads the velocity to have an asymptotic behaviour that is \( \propto 1/\sqrt{r} \). Instead, as we can see in 1.1, at large distances it exhibits a flat behaviour, with \( v(r) \) almost constant. This observation lead to think of the existence of a dark matter halo with mass density \( \rho_{DM}(r) \propto 1/r^2 \) at large radii.

![Figure 1.1: Rotation curve of the galaxy M33. In the plot it can be seen the comparison between the data expectation from the visible disk, and the measures from the visible stars and from the Doppler shift obtained from the Hydrogen 21 cm line.](image)

1.1.2 Bullet Cluster

The Bullet Cluster (1E0657-558) is the first galaxy cluster analyzed with the technique of gravitational lensing. Using the distortion of a far galaxy by the gravitational field from a massive cluster, the estimation of the mass profile of a foreground massive object can be done with the lensing. Combining this technique with other observational data as spectra in the visible and X-ray, it permits to reconstruct the positions of all components in the colliding clusters, such as gas, visible matter and gravitational-interacting matter.

In 1.2 it can be seen the results of the images combination: the hot gas (in 1.2a in pink, while in colours from red to blue in 1.2b) emits X-ray due to the friction during the collision, that increases its temperature, and it contains the majority of the baryonic matter. The other galaxies, on the background of 1.2a, are shown in white and orange, with optical images. Thanks to gravitational lensing, then, it is possible to reconstruct the matter profile, shown in blue in 1.2a and as a contour plot in 1.2b. In absence of dark
1.1. Evidences of Dark Matter

Figure 1.2: The Bullet Cluster

(a) Bullet cluster from a composite image. In pink is shown the hot gas detected by Chandra X-ray telescope; the optical image, taken by Magellan and Hubble Space telescopes, shows the galaxies in the cluster, while in blue it can be seen the mass distribution deduced by gravitational lensing.

(b) Contour plot of mass spatial distribution from gravitational lensing, overplotted on Chandra X-ray data that traces hot plasma. It can be seen that most of the matter resides in a location different from the plasma.

mater the lensing effect would follow the baryonic matter profile, i.e. the central X-ray spot, while it seems to be centered in two separate regions aside.

1.1.3 Anisotropies of the Cosmic Microwave Background

The most recent and compelling evidence of the DM existence comes from the measurements of the Cosmic Microwave Background (CMB) anisotropies, made by WMAP and Planck satellites. From the standard cosmological model it is possible to infer some information about DM, thanks to its predictions that are verifiable experimentally with high accuracy. This model and the relative measurements, in particular, are able to give us an estimation of the amount of matter and energy in the universe.

The standard cosmological model

The standard cosmological model [1] comes out from the solutions of Einstein’s equations in a homogeneous, isotropic universe, developed by Friedmann, Lamaitre, Robertson and Walker (FLRW). In the FLRW model, the metric can be written as:

$$ds^2 = g_{\mu\nu}dx^\mu dx^\nu = -d\tau^2 + a^2(\tau)\left(\frac{dr^2}{1-kr^2} + r^2d\theta^2 + r^2\sin^2\theta d\phi^2\right)$$ (1.1)

where the parameter $k$ describes the curvature of the universe ($k = -1$ for a hyperbolic universe, $k = 0$ for a flat universe, and $k = 1$ for a spherical one), while $a(\tau)$ is the scale factor deriving from Einstein’s equations that absorbs the dependency of $k$ from time.
1.1. Evidences of Dark Matter

In this way, it is possible to have a metric $g_{\mu\nu}$ to be into the Einstein’s equations:

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R - \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu} \tag{1.2}$$

being $R_{\mu\nu}$ the Ricci curvature tensor and $R$ ($g_{\mu\nu} R^\mu\nu$) the Ricci scalar, $G$ the gravitation constant, $T_{\mu\nu}$ the stress tensor, and $\Lambda$ is the cosmological constant. This last term was inserted by Einstein “manually”, just for the purpose to have a static universe, as it was in fashion at that time, but without any other physical reason. Going further with the equations, the stress tensor $T_{\mu\nu}$ for a perfect fluid, as in the FLRW model, can be written as:

$$T_{\mu\nu} = (p + \rho) u_\mu u_\nu - p g_{\mu\nu} \tag{1.3}$$

This is the most general form to describe the tensor in a homogeneous and isotropic model. This perfect fluid is without viscosity, without heat flux, and $u_\mu$ is the fluid four-velocity, $p$ the pressure and $\rho$ the matter density.

To determine the dynamic evolution of the universe having the characteristics described until here, all the equations written above can be combined to form the Friedmann equations:

$$\left(\frac{\dot{a}}{a}\right)^2 + \frac{k}{a^2} = \frac{8\pi G}{3} \rho_{\text{tot}}$$
$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3} (\rho_{\text{tot}} + 3p) \tag{1.4}$$

Here, $\rho_{\text{tot}} = \rho_m + \rho_{\text{rad}} + \rho_{\Lambda}$ are the matter, the radiation and the vacuum energy terms, being $\rho_{\Lambda} = \Lambda/8\pi G$.

From the WMAP/Planck measurements it results that the curvature parameter $k$ is equal to zero, therefore indicating that our universe is flat or nearly flat. Using this measure and the assumptions that, for an ideal fluid, $p = \omega \rho$ for every density, being $\omega$ a constant, the scale factor temporal behaviour can be inferred:

- considering only non-relativistic matter ($v << c$) and $p \propto v$, so $\omega = 0$ and $a(t) \propto t^{2/3}$;
- for radiation, $v = c = 1$ and $p = \rho/3$ (because the pressure is averaged by three spatial terms), so $\omega = 1/3$ and the scale factor $a(t) \propto t^{1/2}$;
- in the vacuum dominant regime, instead, $p = -\rho$, so $\omega = -1$ and $a(t) \propto e^{Ht}$, with $H \equiv \frac{\dot{a}}{a}$ being the Hubble parameter.

In this simplified scheme, it can be deduced the behaviour of the universe during its expansion, from the radiation regime in the first stage, followed by the matter regime until the current vacuum dominated regime.

$\Lambda$ Cold Dark Matter

There has been many attempts to characterize the dark matter starting from a cosmological point of view, including the Lambda Cold Dark Matter ($\Lambda$CDM) model, that is currently
the most accredited one. This model proposes that the dominant part of the matter in the universe is non-relativistic, non-luminous matter. To better understand the \( \Lambda \)CDM model, one has to go back to the Friedmann equation 1.4 and put \( k = 0 \) and \( \Lambda = 0 \). In this way, it is possible to define a critical density:

\[
\rho_{\text{crit}} = \frac{3H^2}{8\pi G}
\]

which can be used to define an adimensional density parameter:

\[
\Omega_{\text{tot}} = \frac{\rho_{\text{tot}}}{\rho_{\text{crit}}}
\]

Thanks to this parameter, the first of the two equations 1.4 can be rewritten as:

\[
\frac{k}{H^2 a^2} = \Omega_{\text{tot}} - 1
\]  

This equation leads directly to a link between the universe geometry and its evolution: if \( k = 1 \) and \( \Omega_{\text{tot}} > 1 \), the universe is closed, if \( k = -1 \) and \( \Omega_{\text{tot}} < 1 \) the universe is open, while if \( k = 0 \) and \( \Omega_{\text{tot}} = 1 \) the universe is flat. These names derive from the features of the scenario they present, as it can be seen in Figure 1.3: a close universe is characterized by the fact that its expansion will stop and change direction, going toward a Big Crunch, while on the opposite an open universe will continue its expansion forever increasing the speed of this expansion. Finally, a flat universe is a scenario where the universe continues its expansion slower and slower.

\[\begin{align*}
(a) \quad &The \ geometry \ of \ the \ universe \\
(b) \quad &The \ evolution \ of \ the \ universe
\end{align*}\]

\textbf{Figure 1.3:} The evolution of the universe based on its geometry

In the term \( \Omega_{\text{tot}} \) all the aforementioned contributions of matter, radiation and vacuum energy are present. The critical density is then the density needed for the universe to have a flat curvature. In this model, cold dark matter (CDM) is a form of matter introduced in order to take into account all the gravitational effects observed: it should be cold, that is non-relativistic, non-baryonic, dissipationless (that is, it can not cool by radiation of photons), and collisionless.
1.1. Evidences of Dark Matter

The Cosmic Microwave Background

The presence in the universe of the modeled cold dark matter on cosmological scale implies the existence of acoustic temperature fluctuations in the Cosmic Microwave Background (CMB). CMB was first detected and discovered by Arno Penzias and Robert Wilson in 1964, and very soon identified as the relic radiation coming from the epoch of decoupling of light and matter, about 380'000 years after the Big Bang, when electrons and protons formed the first atoms. This discovery laid down every other cosmological models but the Big Bang one, and pushed scientists to improve the technology of detection to understand this radiation, from the almost isotropic radiation detected by Penzias and Wilson, to the measurements of anisotropies at $10^{-5}$ level of the most recent satellites.

The Big Bang model says that the universe was born from a spacetime singularity, the Big Bang, at incredibly high energy and temperature, and then it expanded and decreased in temperature, reaching the matter distribution that it can be seen now. From this model, one can have a picture of the different evolution phases:

- few µs after the Big Bang, the $T \approx 10^{15}$ K, with such a high energy density to prevent quarks and gluons to hadrons. This is the quark gluon plasma phase.

- The hadronization could come only $10^{-4}$ s after Big Bang, when the temperature had lowered to about $2 \times 10^{12}$ K.

- After 3 minutes, $T \approx 10^{9}$ K, all the unstable hadrons are already decayed and the antimatter is completely annihilated. Here it comes the primordial nucleosynthesis, in which the first light nuclei form.

- When the universe temperature decreases down to $3 \times 10^{3}$ K, about 380'000 years after the Big Bang, the recombination begins. This is the moment when photons and matter are no more coupled and the universe becomes transparent to light. It is exactly this first light that we can today detect as CMB, carrying us the information about that time.

- $10^{9}$ years after the Big Bang, the gravitational attraction caused the first galaxies formation, reaching step by step the present configuration.

CMB anisotropies are the trace of temperature fluctuations in the early universe, before nucleosynthesis, when quantistic fluctuations permitted to matter (both baryonic and non-baryonic) to distribute quasi homogeneously. But, while the DM kept getting compressed under gravitation, baryonic matter and photons interacted with each others, with expansion and compression of matter under the variations of radiation pressure. It is this interaction between baryonic matter and photons that caused the differences in temperature, that still can be seen in the sky with satellites as WMAP [4] [5] and Planck [6] [7] (see Figure 1.4).

Temperature anisotropies can be expressed by spherical harmonics expansion:

$$T(\theta, \phi) = \sum_{lm} a_{lm} Y_{lm}(\theta, \phi)$$

(1.6)
1.1. Evidences of Dark Matter

Figure 1.4: CMB anisotropies detected by WMAP satellite

\[ a_{lm} \text{ are complex coefficients and } l \text{ is the multipole moment. With this expansion, it is possible to extract the resultant power spectrum, represented as} \]

\[ l(l+1)\frac{C_l}{2\pi}, \quad C_l \text{ being } \quad C_l = \frac{1}{2l+1} \sum_m |a_{lm}|^2 \]

The comparison between the model used by the Planck collaboration and their data is shown in Figure 1.5. The model uses six parameters and describes a flat, expanding universe that follows the laws of general relativity and is dominated by the cosmological constant \( \Lambda \) and cold dark matter. They found that the CMB anisotropies fit a model with \( \Omega_{DM} = 0.2608 \pm 0.0059 \) at 68% CL. Furthermore, it could be possible to calculate the single contribution of baryonic matter \( \Omega_b = 0.04879 \pm 0.0007 \), with a Hubble parameter of \( h = 0.673 \pm 0.012 \).

The essential observation is that \( \Omega_{DM} \) and \( \Omega_b \) are different, meaning that baryonic matter is not the only form of matter in the universe. In fact, the dark matter density is around 83% of the total mass density and corresponds to an average density of \( \rho_{DM} \approx 0.3 \text{GeV/cm}^3 \approx 5 \times 10^{-28} \text{kg/m}^3 \). Because dark matter and baryonic matter act so differently, as above described, the analysis of the CMB allows for a discrimination between them. Figure 1.6 demonstrates this point extremely well; small shifts in the baryon density result in a CMB anisotropy power spectrum (a graphical method of depicting the CMB anisotropies) which are wholly inconsistent with WMAP and other CMB experiment data.
1.1. Evidences of Dark Matter

Figure 1.5: Temperature spectrum as a function of the multipole moment $l$. In red, it can be seen the prediction from $\Lambda$CDM model, while in blue the measurement made by the Planck collaboration. The figure on the top part shows the temperature spectrum, while the bottom one shows the residuals.

Figure 1.6: WMAP data (in red) and different assumptions on the $\Omega_b$ value in the CMB anisotropy power spectrum.
1.2 Candidates for dark matter

1.1.4 Alternatives to dark matter: the MOND model

During these years, several models have been proposed to explain the anomalies, as an alternative to the introduction of new, non-baryonic matter. One of the most promising was the MOdified Newtonian Dynamics (MOND) [8], created in 1983 by the physicist Mordehai Milgrom in order to explain the velocities of stars in galaxies larger than expected from standard Newtonian mechanics. Milgrom tried to solve the problem hypothesizing a different behaviour of Newtonian dynamics for extremely small accelerations. In particular, he proposed to modify the second Newtonian law as \( F_N = m \mu(\frac{a}{a_0})a \), where \( \mu \) is a function of acceleration \( a \) and \( a_0 \), a new constant which marks the transition between the standard Newtonian regime and the MOND regime. This function then can be built empirically, knowing the constrains put by astronomical observations. This simple law provides predictions for several physics phenomena, but since the DM evidences became cosmological, that is with the CMB anisotropies well-explained by the \( \Lambda \)CDM model, the alternative schemes as the MOND theory fastly lost its attractiveness.

1.2 Candidates for dark matter

As said at the beginning of this chapter, the Standard Model of particles does not provide any reliable candidate for DM. Let us summarize all the characteristics that are needed for a dark matter particle:

- it should be **dark**, that is it should not appreciably interact with photons;
- it should be **weakly interacting** with ordinary matter;
- it is necessary that is **massive** and **stable**, or at least very long lived on cosmological time scale;
- and also should be **non-relativistic** (cold\(^1\)).

This last feature is the one that completely excluded the idea that ordinary neutrinos could be good candidates for DM, notwithstanding that are the only particles in the Standard Model that fulfill the other criteria. Apart from being too light for providing a sizeable contribution to the total universe mass, the crucial point is that they are relativistic, while from simulations it can be understood how not being relativistic is fundamental for structures formation.

In Figure 1.7 can be seen the outcome of some simulations of the universe large scale structures.

What is mostly significant is that, in simulations where only hot dark matter (that is, neutrinos, for instance) is present, the emerging structures do not fit the light distribution that can be seen in the actual universe. On the contrary, if only cold dark matter is included into the simulations, the resulting structures resemble the real distribution in a much better way. This result points to the need of considering as DM candidate a particle

\(^1\)The other case (that is, relativistic dark matter) is called “hot”.

1.2. Candidates for dark matter

(a) Cold (CDM) and Hot (HDM) dark matter simulations

(b) Large scale structures data (blue) and simulations (red) [9]

(c) The large scale distribution of light (left) and of cold dark matter (right), from Millennium Simulation

Figure 1.7: Simulations of structures formation and dark matter distribution

outside the Standard Model.

Let us now examine some of the main candidates that are on the scene to give a contribute to dark matter, including the subleading ones.

1.2.1 Baryonic dark matter

The idea that dark matter could be baryonic, ordinary matter but with no emission of light (and so essentially invisible by our telescopes) is now slightly outdated. The hypothesis of dark matter made of collapsed stars, brown dwarfs, neutron stars, collectively called MAssive Compact Halo Objects (MACHOs), has been investigated with microlensing, a technique that involve the use of the gravitational lensing. If a small, dark object passes between our point of view and a star, the gravitational lensing effect caused a temporary, apparent rise of luminosity of the star; it is needed, therefore, that the star chosen is not
variable. The MACHO [11] [12] and EROS [10] experiments were able to put strict constraints on the abundance of this kind of dark matter in the universe, namely below 20 and 8%.

1.2.2 Primordial Black Holes

A primordial black hole is a hypothetical type of black hole different from those deriving from the gravitational collapse of a large star, but generated during the first stages of the universe, because of the extreme density fluctuations of the matter.

Black holes are regions of the spacetime showing a gravitational field so strong that nothing, neither particles nor even light, can escape from inside. A black hole can be generated after gravitational collapse of a star with a mass larger than $20M_{\odot}$.

Thus, it is noticeable that a black hole is an object that can interact only gravitationally even if it has a baryonic composition. This can lead to think that black holes could be a good candidate to contribute as DM in the universe, but known black holes generate after a star collapsing while, as simulations show, DM is needed before Large Structures in the universe began to form. This, among others considerations, makes one think that black holes could still be good candidates only if considering their formation during the early stage of the universe, when temperature and pressure were extremely high. Under these conditions, simple fluctuations in the density of matter may have resulted in local regions dense enough to create black holes. Although other regions of high density would be quickly dispersed by the expansion of the universe, a large enough primordial black hole would be stable, persisting to the present.

Even if the idea is attractive, quantitative details of abundance and stability of these objects depend crucially on a theory, the quantum gravity, that still is largely unknown. During last year, after the first detection of gravitational waves at the LIGO observatory [23], the interests for black holes giving a large contribution to DM in the universe has come to the fore again [22].

1.2.3 Neutrinos

For some years, neutrinos have been thought as a good candidate for dark matter, until simulations as the one in Figure 1.7a have clarified that they cannot be because they are relativistic. Moreover, there are limits on neutrino mass that put constrain on the abundance in the universe below to $\Omega < 0.016$. It still remains the possibility, however, of sterile neutrino as a possible candidate [13]. Sterile neutrino is a particle beyond the Standard Model, introduced in order to explain the neutrino oscillation problem, and its range mass is still under discussion. It should be hypothetically the right-handed neutrino, that can only interact by gravity. They are an attractive candidate for new particle, because they can explain not only the dark matter problem, but also baryon asymmetry and neutrino oscillations. This model, though, requires experimental tests. Moreover, in the neutrino oscillation framework, the sterile neutrino needs to be lighter than requested for the dark matter contribution.
1.2. Candidates for dark matter

1.2.4 Axions

Axions have been first postulated to solve the strong CP problem, consisting in the observation that strong interactions seem to respect CP symmetry while, according to QCD, a violation of CP symmetry in the strong interaction should be expected. Peccei and Quinn, in 1977, proposed a solution based on a quasi-symmetry, respected at classical level but spontaneously broken by an axion field [14]. The axion mass is predicted to be inversely proportional to the vacuum expectation value that break CP symmetry.

There are two main methods in detecting axions: one is based on production of axions in laboratories, and the other to detect them from a natural source, as the Sun. Both of these methods rely on the idea that axions can have an interaction diagram with two photons, which allows for the conversion between axions and photons in a strong electromagnetic field. Several experiments using techniques related to this axion-photon conversion are underway to search for axions in the mass range of less than 1 eV, some possibly reaching the $10^{-4}$ to $10^{-6}$ eV range [15].

1.2.5 Weakly Interacting Massive Particles

Weakly Interacting Massive Particles (WIMPs) are a class of hypothetical particles, non-Standard Model and non-relativistic, that interact with standard particles through weak nuclear force or interactions similar in strength. Their mass is typically assumed to be between $\sim 10$ GeV and few TeV. The fact that WIMPs have the characteristic relic abundance determined by the thermal freeze-out method is the main reason of WIMP to be one of the preferred candidates.

Thermal freeze-out

Based on the assumptions that WIMPs exist, let us think about the production process in the early stages of the universe formation, while it expanded and cooled (Figure 1.8). The evolution of the number density of thermal relic particles, indicated as $n_\chi$, follows the Boltzmann equation:

$$\frac{dn_\chi}{dt} = -3Hn_\chi - n^{eq}_\chi n^{eq}_\chi < \sigma_{\chi\chi \rightarrow q \bar{q}} v > \left( \frac{n^{eq}_\chi n^{eq}_{\bar{q}}}{n^{eq}_\chi n^{eq}_{\bar{q}}} - \frac{n_q n_{\bar{q}}}{n_q n_{\bar{q}}} \right)$$

(1.7)

where $H = \frac{\dot{a}}{a}$ is the Hubble parameter, $n^{eq}$ is the thermal equilibrium dark matter number density, and $< \sigma_{\chi\chi \rightarrow q \bar{q}} v >$ is the thermally averaged annihilation cross section to the standard model particle (q) times velocity. Now it is possible to make the assumption that dark matter is in particle-antiparticle equilibrium, and furthermore that the term $\frac{n_q n_{\bar{q}}}{n_q n_{\bar{q}}}$ is equal to one, meaning that standard model particles are repopulated through other channels. It can be written, in this case:

$$\frac{dn_\chi}{dt} = -3Hn_\chi - < \sigma_{\text{ann}} v > \left( (n_\chi)^2 - (n^{eq}_\chi)^2 \right)$$

(1.8)

The first term in the right part of the equation means that while the universe expand, the dilution of the density $n_\chi$ occurs, while the second term has been summed over all channels
1.2. Candidates for dark matter

Figure 1.8: A representation of the freeze-out for a WIMP particle of mass 100 GeV. On the x-axis, on the top the time while on the bottom the energy at which the freeze-out happened, while on the y-axis there are the density of particle, on the left, and the $\Omega_\chi$ on the right.

to account for dark matter annihilation to SM particles (the $n_\chi$ term) and the dark matter annihilation to thermal relics ($n_{eq}\chi$). As the universe expands, the first term increases while the second one becomes negligible, so that effectively no more annihilation of thermal relic could happen (here the name “freeze-out”). Writing $\Omega_\chi$ as a function of $n_\chi$ and solving the Boltzmann equation, one can find:

$$\Omega_\chi = \frac{\rho_\chi}{\rho_{\text{crit}}} = \frac{m_\chi n_\chi}{\rho_{\text{crit}}} \sim \frac{x_f T_0^3}{\rho_{\text{crit}} M_{\text{Pl}} < \sigma_{\text{ann}} v >} \sim 6 \times 10^{-27} \text{ cm}^3\text{s}^{-1}$$

where $x_f$ is the ratio of the thermal relic mass to freeze-out temperature, $T_0$ is the present temperature of the universe, $\rho_{\text{crit}}$ is the critical density and $M_{\text{Pl}}$ is the Planck mass [47]. The most remarkable fact is that from cosmological observations it turns out to be $\Omega_{DM} \approx 0.23$, so that $< \sigma_{\text{ann}} v > \approx 3 \times 10^{-26} \text{ cm}^3\text{s}^{-1}$. This means that the annihilation cross section for any thermally created particle is just what would be predicted for particles with electroweak scale interactions, $< \sigma_{\text{ann}} v > \approx \left( \frac{9 g^2}{4 \pi} \right)^2 M^2$.

From this result, one can also infer the mass of the dark matter particle, that should be around 100 GeV.

1.2.6 Supersymmetric Candidates

Supersymmetry (SUSY) is a theory beyond the Standard Model proposing a symmetry between bosons and fermions, that introduces supersymmetric partners for all particles in the SM. The SUSY partner of a SM particle is a heavier particle which differs in spin by 1/2. The fundamental quantity for the SUSY model is the R-parity, defined as $R = (-1)^{3B+L+2s}$ being L the lepton number, B the baryonic number and s the spin of the particle. This R-parity value for Standard Model particles is +1, while their supersymmetric partners
have -1. If the R-parity is a conserved quantity, the lightest SUSY partner particle should be stable and operate at the thermal freeze-out mechanism. Candidates for dark matter are the lightest neutralino, which should be a Majorana fermion, or the gravitino (partner of the graviton).

1.3 Techniques for Dark Matter Search

There are three main ways to detect dark matter, each based on the assumption that DM and SM particles can interact somehow. In Figure 1.9, it can be seen a scheme for the detection techniques of DM.

![Figure 1.9: Scheme for DM detection techniques](image)

1.3.1 Collider Search

The search at colliders follows the principle that, if this scheme is correct, one can see production of DM particles from interaction of SM particles. High energy physics colliders as LHC, at CERN, produce showers of particles, some of which could interact and become dark matter and could be detected from missing transverse energy.

1.3.2 Indirect Detection

Dark matter could also be detected in the reverse case. If DM particles interact with each other, they can produce SM particles; this can happen in those places of the universe where dark matter is more concentrated (Galactic Center, Earth's core) and the annihilation process can mostly occur. Dark-matter annihilations into SM particles would produce an equal numbers of particles and antiparticles. The observation of antiparticles is therefore a potential clue for indirect detection of dark matter. Several experiments with positron detectors, with the aim of observing some excess in positron-to-electron ratio, have taken anomalous data but still inconclusive. AMS [16], PAMELA [17], ATIC [18]: all (and more) of them have seen unexplained but conflicting particles flux excess.
1.3. Techniques for Dark Matter Search

1.3.3 Direct Detection

Direct detection looks for DM particles interacting with SM particles. In this interaction, some of the energy of DM particle can be ceded to the SM particles: to see this energy, one can use methods developed for observing energy deposits from other kind of radiation. Dark matter direct search has many aspects in common with rare events physics, having the same need of low radioactive background and very low energy threshold.

WIMP event rate

WIMP dark matter is assumed to scatter elastically against atomic nuclei. On a detector Earth-based, a WIMP scatter-off with a target nucleus, and the particle hit by the WIMP recoils with an energy $E_R$. If the recoil energy is large enough, it is possible to infer from its kinematics some of the properties of the particle that scattered off it. Let us take $E_R$ as recoil energy, $M$ the mass of the nucleus and $m_\chi$ the mass of the incoming WIMP:

$$E_R = \frac{\mu_\chi^2 v^2 (1 - \cos(\theta_{cm}))}{M}$$

where $\theta_{cm}$ is the scattering angle in the center-of-mass frame, $\mu_\chi = \frac{M m_\chi}{M + m_\chi}$ is the reduced mass of the system nucleus-WIMP, and $v$ is the relative velocity between WIMP and nucleus. Taking $v \sim 220 - 230$ km/s as the characteristic WIMP velocity with respect to the Sun, $E_R$ for a 10-1000 GeV/c$^2$ WIMP will be between 1-100 keV. That is the typical energy scale that detector for direct search should be sensitive to. It is noticeable that the nuclear binding energy is about 1-10 MeV, so the DM particle effectively scatter off the nucleus, and not the constituents.

It is possible to express the differential event rate per unit detector mass as [19]:

$$\frac{dR}{dE_R} (E_R, t, m_\chi, \sigma) = \frac{n_\chi}{M} < v \frac{d\sigma_{WN}}{dE_R} > \frac{\rho}{M m_\chi} \int_{v_{\min}}^{v_{\max}} f(v, t) \frac{d\sigma_{WN}}{dE_R} (v, E_R) dv$$

where $\rho_\chi$ is the local WIMP density and $n_\chi$ the number density, $d\sigma_{WN}/dE_R$ is the differential cross section for the WIMP-nucleus elastic scattering, $f(v, t)$ is the normalized WIMP speed distribution. Here it is taken the Standard Halo Model that assumes an isothermal, isotropic, spherical dark matter halo with a Maxwellian distribution of velocities, with velocity dispersion $\sigma_v$ in the galactic rest-frame. Thus, $v_{\min} = \sqrt{\frac{M E_R}{2 \mu^2}}$ is the minimum WIMP velocity needed to produce a scattering with recoil energy $E_R$, while $v_{\max}$ is the escape velocity of stars from the galaxy, and it is around 500-610 km/s at 90% confidence level [20].

The event rate of a WIMP scattering in a dark matter detector will be very low: several different factors contribute to the exact event rate, from particle and nuclear physics to astrophysics. From astrophysics, for example, one can derive the $v_{\min}$ and $v_{\max}$, or the density $\rho_\chi$. From particle and nuclear physics, instead, it is possible to write the
1.3. Techniques for Dark Matter Search

WIMP-nucleus cross section in terms of quarks and gluons in order to describe the different WIMP-field, 1/2 or 1, interacting with the detector. This is useful because in this way the cross section can be separated in two summed contributes, that are one for a spin-independent (SI) and one for a spin-dependent (SD) interaction:

$$\frac{d\sigma_{WN}}{dE_R} = (\frac{d\sigma_{WN}}{dE_R})_{SI} + (\frac{d\sigma_{WN}}{dE_R})_{SD} = \frac{m_N}{2\mu^2v^2}(\sigma_0^{SI}F_{SI}^2(E_R) + \sigma_0^{SD}F_{SD}^2(E_R))$$  \hspace{1cm} (1.12)

where $F(E_R)$ are the nuclear form factors representing the momentum transfer, while $\sigma_0^{SI,SD}$ are the WIMP-nucleon cross sections when the momentum transfer tends to zero. In these terms is contained the information about the material used as a target. As a matter of fact:

$$\sigma_0^{SI} = \frac{4\mu^2}{\pi}(Zf_p + (A-z)f_n)^2$$  \hspace{1cm} (1.13)

$$\sigma_0^{SD} = \frac{32\mu^2}{\pi}G_F^2J + 1 J(-a_p < S_p > + a_n < S_n >)$$  \hspace{1cm} (1.14)

with $G_F$ the Fermi coupling constant, $f_{p,n}$ and $a_{p,n}$ being the effective WIMP coupling constant to protons and neutrons, and $< S_{p,n} >$ are the expectation values of spin operators for protons and nucleons, in the limit of zero momentum transferred.

Sensitivity and State-of-the-Art of Direct Detection Experiments

If an astrophysical and a nuclear model can be assumed, it is evident from Equation 1.12 that the differential event rate is determined only by the WIMP mass and the energy-independent cross section. Hence, it can be determined a parameter-space region in the WIMP mass/cross section plane, from a energy spectrum of nuclear recoil events in a given detector:

$$N = n_{tgt}\sigma\Phi \rightarrow n = \frac{N}{n_{tgt}} = \sigma\Phi$$  \hspace{1cm} (1.15)

where $n_{tgt}$ is the number of target nuclei, $N$ is the number of events per second, $\sigma$ the cross section and $\Phi$ the flux, both depending on the WIMP mass. In the right-hand side of 1.15, it can be seen that it is possible to reach the target-independence, necessary to compare different experiments with different detection methods (further details will be given in the next paragraph). Figure 1.10 represents the current situation in the dark matter direct search, in a spin-independent scenario, taken the $\Lambda$CDM astrophysical model and the Standard Halo Model. With the help of this Figure, it can be understood how to read an exclusion plot:

**case a:** if the detector observes $N$ events in excess respect to the expected background, a closed contour is drawn in the $(\sigma, M)$-plane;

**case b:** if no events are seen by the detector in excess of background, an open contour is drawn in the plane, excluding the area above.
Figure 1.10: State-of-the-art of the current experiments for dark matter search with direct detection techniques in a spin-independent scenario, taken the $\Lambda$CDM astrophysical model. The yellow region on the bottom is the neutrino coherent scattering limit, depending also on the target used.
It is crucial to understand that this way to compare different experiments is based on several assumptions, from the DM halo, to the DM candidate (WIMP), the nature of interaction (spin-independent) and the target of interaction (nuclei). In this framework, the worldwide effort for the dark matter search is orientated to a multiple-target approach, useful because it permits to explore all the parameter-space region, and because it can underline specific material sensitivities to dark matter coupling.

Clearly, the possibility for a comparison can also lead to some tension among different experiments. Still in the Figure, it can be seen that some region taken as closed contour, are excluded from the open plot of other experiments. It is mandatory to keep in mind, while examining these plots, that the differences in the same data-sets from two experiments can be enhanced or reduced taking different interaction models.

Types of Direct Detection

There are several methods to detect WIMP-nucleus dissipation of energy in the media. This dissipation can occur into a material that, under excitation and de-excitation of the electrons of its atoms, emits light (scintillator). Or it can happen that the recoiling nucleus ionizes the molecules around it; another way is the dissipation of energy as heat. Different detection methods take advantages from different techniques when searching dark matter hints.

**Figure 1.11:** Techniques for the direct dark matter search

**Scintillation**

Scintillators are various types of material with the characteristic that, when there is some energy deposit in them, they emit visible or UV photons. This is due to the excitation and, consequently, de-excitation of the electrons of the atoms in the medium, with a specific decay time. In general, the number of photons released per interaction is proportional to the energy deposited in the medium, but there are many exceptions and non-linearities. Moreover, different particles interact in a different way with the scintillator, with number of photons and length of the track
depending on which particle scattered. The incident particle can interact not only by imparting energy to electrons but also doing nuclear recoil. While dark matter is supposed to interact mostly with nuclei, background due to charged particles only generate electron recoil. The relative scintillation response between electron and nuclear recoils is characteristic of the material and is referred to as the quenching factor, $Q$, which can be energy dependent. With calibration, it is possible to define the region of interest for nuclear recoils for a dark matter search.

It is needed to characterize the scintillation response of a material independently of the interaction type: the unit keV-electron-equivalent ($\text{keV}_{ee}$, or $\text{MeV}_{ee}$, or $\text{eV}_{ee}$, etc.), is used to describe the energy that produces the same scintillation response as an electron recoil with that energy. For electron recoils, the $\text{keV}_{ee}$ and keV are equivalent, while for nuclear recoils, they are related by the quenching factor $1 \text{ keV} = Q(E_R) \text{ keV}_{ee}$.

To detect light from low energy events it is required a detector sensitive to the single photon: this is usually achieved with a PhotoMultiplier Tube (PMT). PMTs consist in a series of dynodes within a vacuum chamber, with a window coated with a material (photocathode) that permits to photons to convert in electrons thanks to photoelectric effect. The electron released by the photocathode is accelerated against the first dynode by a potential difference applied by external voltage supply source. The voltage is applied to a voltage-divider chain that keep increasing the voltage from each dynode to the next one. When the electron impinges on the first dynode, the multiplication begins and a cascade of electrons from secondary emission is produced. By the time the electrons reach the last dynode, it is accomplished a gain in charge of around $10^6$ or more (depending on voltage applied), that produces a current detectable at the PMT anode.

For dark matter direct search experiments, some PMT features are particularly important, such as the gain, the quantum efficiency, the collection efficiency and the dark rate. The gain is the ratio between the amount of charge (or current) collected by the PMT with respect to a single photoelectron emitted by the cathode. The quantum efficiency is the percentage of photons that are successfully converted into electrons after striking the photocathode, while the collection efficiency is the chance, for a photoelectron, to hit the first dynode and to begin the cascade. Typically, quantum efficiency is around 20-40\% depending on the photocathode material. The collection efficiency is instead around 80\% or higher.

**Ionization**

A recoiling nucleus can ionize the nearby atoms and generate free electrons in the medium. To collect the electrons, it can be applied a strong, electric field, and then the signal can be detected. There are several ways to use ionization for the dark matter search: one of the most popular is, for instance, the noble gas dual phase Time Projection Chamber (TPC). It consists in a large volume of a noble element in a liquid phase, and on the top of the volume the same element but in a gas phase. On the top and at the bottom of the volume, arrays of PMTs are looking at the detector.
1.3. Techniques for Dark Matter Search

A strong, uniform electric field is applied to the volume, drifting upward the electrons generated from the ionization. After a prompt scintillation light in the liquid phase, a second signal due to scintillation into the gas phase follows. The ratio of the two signals allows to discriminate the type of recoil, nuclear or electron. Moreover, the detector allows a 3D identification of the position thanks to the reconstruction of the arrival time of the electrons.

**Temperature**

Cryogenic technique is based on the idea that a small amount of heat is dissipated from a recoiling nucleus. This leads to detection of WIMP in a medium put in a very low temperature environment, where even small amount of temperature change in the material can be detected thanks to sensitive heat sensors. The temperature change is thus equal to the energy losses by the particle in the recoil, if all the energy is dissipated as heat.

They can use also light detectors, in order to compare the energy detected by heat sensors versus the energy detected by light emitted. This makes possible also the identification of the particles that hit the detector (Figure 1.12), as nuclear recoiling particles such as WIMPs generate less scintillation light with respect to electron recoiling particles such as charged backgrounds.

![Figure 1.12: Particle identification with Pulse Shape Discrimination in CRESST experiment [21]](image)

**Annual Modulation**

Back to 1.12 again, let us discuss the time-dependence of the scattering rate, arising from the boost of the velocities in the lab system of reference. Assuming a net-zero velocity for the DM halo with respect to the Galactic center, there is a constant $\sim 220 \text{ km/s}$ “wind” of DM in the Solar frame (Figure 1.13) due to the movement of the Solar System through the galaxy. Moreover, the Earth orbiting around the Sun at $\sim 30 \text{ km/s}$ moves into the DM wind during summer, and away during winter. Flux and cross section of WIMP-nucleus
scattering both depend on velocity, so a ground-based detector on Earth will experience a modulation in event rate, with a peak in June and the lowest count in December.

Let us see more in details the differential event rate as a function of time, as just discussed. The lab frame velocity distribution is obtained by applying a Galilean boost to the Galactic frame distribution, \( f(v) \):

\[
\tilde{f}(v) = f(v + v_{\text{obs}}(t)), \text{ where } v_{\text{obs}}(t) = v_{\text{Sun}} + v_{\text{Earth}}(t)
\]

\( v_{\text{Sun}} \) is the velocity of the Sun in the DM halo, while the term \( v_{\text{Earth}}(t) \) is the Earth's velocity around the Sun. As it was already said, \( v_{\text{Sun}} \sim 220 \text{ km/s} \), while \( v_{\text{Earth}}(t) \sim 30 \text{ km/s} \). To good approximation, it is possible to write:

\[
v_{\text{obs}}(t) \approx v_{\text{Sun}}(1 + \frac{v_{\text{Earth}}}{v_{\text{Sun}}} \cos[\omega(t - t_0)]) + \ldots
\]

with \( \omega = \frac{2\pi}{\text{year}} \), \( t_0 \) is the modulation's phase, and \( v_{\text{Earth}}^\perp \) is the component of the Earth's velocity in the Sun's direction. Because \( v_{\text{Earth}}^\perp \ll v_{\text{Sun}} \), it is possible to expand with Taylor to obtain:

\[
f(v + v_{\text{obs}}(t)) \approx f(v + v_{\text{Sun}}) + \frac{v_{\text{Earth}}}{v_{\text{Sun}}} \cos[\omega(t - t_0)]f'(v + v_{\text{Sun}}) + \ldots
\]

So that the rate equation takes the form:

\[
\frac{dR}{dE_R} = A_0 + A_1 \cos[\omega(t - t_0)] + \ldots \tag{1.16}
\]

where the term \( A_0 \) is the unmodulated rate, and \( A_1 \) describes the annual modulation of the signal. The higher orders of the expansion are interesting only in case of light DM (\( \leq 10 \text{ GeV} \)) or in case of velocity substructures.

Another effect to take into account is the gravitational lensing caused by the Sun gravitational field, that deflects the dark matter on its way to Earth. In particular, looking at
Figure 1.14: The gravitational lensing effect on the annual modulation

Figure 1.14, during spring the dark matter particles are pulled together increasing the flux, while during fall this effect disappears.

This was initially thought to be a negligible effect, but new studies show that it can shift the modulation phase earlier in the year if $v_{\text{min}}$ is small: a slower average speed of the DM halo with respect to the movement of the Sun is more susceptible to gravitational focusing.

The annual modulation is a signature characteristic of WIMP dark matter, and can be taken as evidence for its existence if observed in a low-background experiment. A high-mass detector with several years of exposure could be sensitive to such a modulation. It is necessary, however, that the running conditions of the detector should be stable enough in order not to mask the effect of the annual modulation. In particular, seasonal effect having 1 year period can be especially dangerous.
Chapter 2

The SABRE experiment

Once the question of dark matter has been opened, many experiments have been built in order to catch some WIMP signal, using different techniques and approaches. However, only one of them could succeed in the discovery, with a claim of a dark matter detection with a high statistical significance. This experiment is DAMA/LIBRA \cite{24} that (combining the results with the previous phase, DAMA/NaI) observes an annual modulation in the 2-6 keV energy region\footnote{More details will be given in Section 2.1}, with a statistical significance of 9.3\(\sigma\) \cite{25}. No other experiment can make a claim as this, but it is also true that no other experiment uses the same sodium-iodide (NaI) target. As already said in the previous Chapter, however, the way to compare different experiments depends strongly on the theoretical model used. For this reason the DAMA/LIBRA claim still remains an open question.

It is therefore necessary to build an experiment using the same target and analysis strategy as DAMA/LIBRA, to answer the question. A NaI(Tl) target must be used, with the same or better radiopurity, with features that can improve the ability to discriminate between dark matter signals and background. Such an experiment can be SABRE (Sodium-iodide with Active Background REjection).

Before to go deeper into details of SABRE experiment, let us do a brief excursus of the DAMA/LIBRA experiment, that is useful to understand not only the claim that they state, but also the problems related to it.

2.1 The DAMA/LIBRA experiment

The DAMA/LIBRA is an annual-modulation dark-matter experiment located at the National Laboratories of Gran Sasso (LNGS) that uses highly radiopure NaI scintillators in an array of 25 10-kg NaI(Tl) crystals as dark matter target. The DAMA experiments, that is, DAMA/LIBRA and its predecessor DAMA/NaI, have been a pioneer activity in the direct search of the dark matter using the annual modulation signature. DAMA/NaI was a \(~100\) kg array of highly radiopure NaI(Tl) crystals, while the DAMA/LIBRA is the upgrade of DAMA/NaI, using \(~250\) kg of highly radiopure NaI(Tl) crystals. Thanks to them, the DAMA experiments have seen for over a decade an annual modulated signal
attributed to dark matter, with a $9.3\sigma$ of statistical significance.

DAMA/LIBRA became operational in 2003, and the first results were released in 2008. In 2010, an upgrade of their photomultiplier tubes had been done, with an expected energy threshold lower than 2 keV$_{ee}$.

### 2.1.1 The DAMA/LIBRA apparatus

As previously said, the experiment consists of an array of 25 NaI(Tl) crystals for a total mass of about 250 kg. The crystals are rectangular prisms, and their two smallest faces are coupled to photomultiplier tubes via 10-cm long synthetic quartz light-guides. Each crystal lays in a copper enclosure flushed by gaseous, high-pure nitrogen, and the set of crystals are surrounded by different layers of passive shielding. The LNGS location and the room conditions in which DAMA/LIBRA is set, permit to have an accurate control of the environment parameters, such as temperature, radioactivity and pressure. A schematic picture of the apparatus can be seen in Figure 2.1. A detailed description of the DAMA/LIBRA apparatus is given in [26].

![Figure 2.1: Schematic representation of DAMA/LIBRA apparatus. Figure from [26]](image)

### The crystals

The crystals used by the DAMA experiments are sodium-iodide doped with thallium. Let us briefly discuss about the scintillation properties of this crystal before to speak about the DAMA ones.

The ideal scintillator material should have some desired features, such as scintillation efficiency in converting the energy of the incident particle into detectable light, a linear light yield with deposited energy, a short decay time, good optical properties... The NaI exhibits the best light output and good linearity, even if the response is relatively slow (compared
2.1. The DAMA/LIBRA experiment

to other types of scintillators: the time constant ranges between 200 and 320 ns. Additionally, the spectral distribution of the scintillation photons has its maximum around 420 nm.

Because of the characteristic of the DM signal, that is expected to be with very low cross section and low recoil energy, the target crystal should be highly radiopure and with high light yield. The first characteristic is needed in order not to obscure or falsificate the dark matter signal with radio-impurities, and the other is needed because is necessary to be sensitive to low energy events where the modulation is expected to occur.

The crystals used from DAMA/LIBRA were grown by Saint Gobain Crystals and Detectors company, with the Kyropoulos method of crystal growth. In this method, a seed crystal is lowered into a crystal melt, the melt is slowly cooled, and the crystal forms around the seed [28]. The most dangerous backgrounds for this crystal (so, both for the DAMA experiments and the SABRE one) and their characteristics: arguably, these are $^{40}$K, $^{232}$Th, $^{238}$U, $^{87}$Rb and the cosmogenics.

$^{40}$K represents a double danger. The $^{40}$K decays with electron capture in $^{40}$Ar (see Figure 2.2) producing a 3-keV$_{ee}$ electron or X-ray occurring in the modulation signal region of DAMA/LIBRA.

![Figure 2.2: $^{40}$K decay scheme](image)

This background can be rejected by observing the corresponding 1461-keV γ released during the de-excitation of the $^{40}$Ar nucleus, if the gamma releases energy in an active volume surrounding the crystal. DAMA measures the $^{40}$K concentration by comparing the rate of 1461-keV$_{ee}$/3-keV$_{ee}$ coincidence events in their crystals and the rate as predicted by a Monte Carlo simulation. The details of this Monte Carlo have never been shared by the DAMA collaboration and conflicts with other attempts to simulate the energy spectrum of that region [29]. Then, the $^{40}$K lies in the same column of the sodium in the periodic table of element, so it is difficult to separate them.

$^{232}$U and $^{238}$Th have long decay chains that produce variety of backgrounds, some of them being in the energy region of interest of DAMA. The estimation of these isotopes concentration is made by DAMA by observing the peaks from characteristic α particles in the decay chain.

Another important and controversial background is $^{87}$Rb, because this is an alkali metal and hard to remove from NaI crystals. DAMA reports limits for this background, but the
2.1. The DAMA/LIBRA experiment

background rate at this limit would constitute a large portion of DAMA’s signal, so it is unclear how prominent of a role they play in the DAMA experiment. Cosmogenics, such as $^{22}$Na, $^{24}$Na and $^{125}$I, are a kind of background that can be fought by housing the crystals for a long period underground before the operation. However, the $^{22}$Na background becomes relevant if an experiment such as DAMA lowers the threshold to 1 keV$_{ee}$, since the $^{22}$Na emits a $\sim$0.8 keV X-ray/Auger-electron with a 9% of branching ratio.

The photomultipliers and crystal housing

The photomultiplier tubes (PMTs) used by DAMA/LIBRA until the upgrade in 2008 were produced by Electron Tubes Limited (ETL), using a bialkali photocathode. The peak quantum efficiency was about 30%, with a dark rate of 100 Hz and a gain around $10^6$ [26]. The new PMTs are Hamamatsu R12669 with higher quantum efficiency (peak $\sim$ 38%) and lower dark rate (<100 Hz). The increased quantum efficiency allowed DAMA to lower the energy threshold below 2 keV$_{ee}$.

The crystals are wrapped with Tetratex Teflon tape, chosen by its radiopurity, and packaged in oxygen-free high-conductivity (OFHC) copper enclosures. The PMTs are also housed in OFHC copper, as it can be seen in Figure 2.3, and are separated from the crystal by a synthetic silica light guide, in order to reduce the radioactive background induced to the crystals. The DAMA crystal detectors have light yields in the range of 5.5-7.5 phe/keV$_{ee}$, including the effect deriving from the use of light-guide [26].

![Figure 2.3: New PMT enclosed and its shaped copper shielding. Figure taken from [24]](image)

The shielding

The DAMA/LIBRA experiment is surrounded by several layers of passive, low-radioactive shielding, in order to protect the detectors from the external backgrounds coming from cosmogenics and from the environment. For the cosmogenic backgrounds, the solution has been found in keeping the material underground before the beginning of the experiment, to allow cosmogenic activated isotopes to decay.
2.1. The DAMA/LIBRA experiment

To shield the detectors from the environment backgrounds, the crystal modules are surrounded by a 10-cm bricks of copper, surrounded in turn to 15 cm of low-radioactivity lead, to block $\gamma$ radiation. The lead is covered by foils of cadmium, that can block thermal neutrons, and finally everything is surrounded by 30 cm of paraffin and polyethylene, good as well to stop neutrons.

To avoid contamination due to radon, a two-layers sealed barriers are set, and the environment around the detector is filled with high-purity nitrogen gas.

The environmental conditions of the apparatus have been carefully monitored by the DAMA group; studies of the effect on the annual modulation signal due to the variations of some environmental variables has been published [30].

2.1.2 Data processing

The DAMA/LIBRA acquisition starts whenever there is a coincident signal in both PMTs [26]. The DAMA rejection of the backgrounds is done via anti-coincidence among crystals and applying Pulse Shape Discrimination techniques.

DAMA/LIBRA asks for the so-called “single-hit events”, rejecting the “multi-hit events” in which the scintillation occurs in more than one crystal at the same time. This rejection is due to the extremely rare interaction of WIMP with baryonic matter: as WIMP multi-interaction is negligible, multi-hit events can be safely discarded as background.

After these requirements, a discrimination between PMTs noise and scintillation signals is done. PMTs noise is faster than true scintillation from the crystal, so the two structures are easily distinguishable. PMT noise are usually single fast photoelectrons, with decay time in order of tens of ns, while the scintillation light has a decay time of hundreds of ns. Figure 2.4 shows this, and in Chapter 3 and 4 more example are provided from the PMTs and the crystal used in this work.

In order to reject noise from PMT and select only scintillation events, two shape parameters are defined, corresponding to the fraction of pulse integral that occurs in the first 50 ns and from 100 ns to 600 ns:

\begin{align}
X_1 &= \frac{\text{Area from 100 to 600 ns}}{\text{Area from 0 to 600 ns}} \\
X_2 &= \frac{\text{Area from 0 to 50 ns}}{\text{Area from 0 to 600 ns}}
\end{align}

Plotting these parameters on the $X_1$-$X_2$ plane, a histogram of the electronic noise events along the scintillation ones can be drawn. As shown in Figure 2.5, though there is a good separation between the two sets of events, still there is some overlap, in particular at lower energies. Moreover, this kind of PSD can not eliminate the background coming from the dynode-afterglow (or afterpulse) effect, but a more sophisticated method is necessary. This phenomenon is due to emission of light from the PMT dynodes that can reach the opposite PMT coupled to the crystal, producing a false coincidence, because the delay of these kind of signals is about 50 ns.
Figure 2.4: Event near the region of 2 keV$_{ee}$ for an electronic noise event (top) and a scintillation signal (bottom). These signals have the same area [26]
Figure 2.5: Electronic noise rejection in DAMA/LIBRA. The front axis is the $X_1$ parameter, the side axis is the $X_2$, so the noise events appear in the top left corner of the plot, being faster than scintillation (so having a small $X_1$ and large $X_2$). On the contrary, scintillation events have larger $X_1$ and small $X_2$. The plots on the left show single-hit events in DAMA’s normal operation mode, while the right plots show the behaviour in presence of a $\gamma$ source, that causes the scintillation to be dominant. In the top plots, the 2-4 keV$_{ee}$ energy region, while in the bottom plots are shown the 4-6 keV$_{ee}$ ones [26].
2.1. The DAMA/LIBRA experiment

The hardware threshold for DAMA is set to 0.2 keV$_{ee}$, that is at single-photoelectron level, but they use a software in which the threshold is 2 keV$_{ee}$ to lower the incidence of PMT noise. With the use of the new PMTs, DAMA says that they can lower the software threshold to 1 keV$_{ee}$.

The energy resolution of their crystals is constantly measured by using a $^{241}$Am source [26], [30], and the efficiency is also periodically measured with the use of the same source. It can be seen the overall efficiency of DAMA/LIBRA in Figure 2.6. The collaboration uses this curve to correct the systematic loss of low-energy events rate.

![Figure 2.6: The DAMA/LIBRA’s reported detection efficiency for the ETL tubes (the black triangles) and the Hamamatsu ones (white circles) [26]](image)

2.1.3 The claim

As previously said, the DAMA experiments have been observing an annual modulation signal for over a decade. The modulation is only in the “single-hit” event rate, and it is shown in Figure 2.7. It carries several of the features expected for a WIMP modulation, such as the phase and the period, within the errors. The observed period is 0.998±0.002 years, and the modulation has a peak around 144±7 days (that is, at the beginning of June) [25].

This modulation appears in the low energy region, between 2 and 6 keV$_{ee}$, and disappears completely at higher energy, as it can be seen in Figure 2.8a. The modulation rate seems to have a peak at $\sim$ 3 keV$_{ee}$, but the falloff of the modulation below 3 keV$_{ee}$ can be a threshold effect. The total rate of single-hit events is also shown in Figure 2.8b, and it does include not only WIMP recoil on the target nuclei, but also a background from radioactive sources.

The statistical significance of the modulation seen is 9.3$\sigma$ in 2013 [25], and until now
DAMA remains the only experiment that can claim to have seen the dark matter. Assuming the Standard Halo Model and the standard “vanilla” WIMP interaction with a spin-independent cross section, the modulation best fits with a \(\sim 80\) GeV WIMP interacting with iodine, or a \(\sim 10\) GeV WIMP interacting primarily with sodium. The first type falls into the definition of supersymmetric WIMP dark matter, while the second is categorized as a “light WIMP” [25]. DAMA claims a positive, model-independent discovery of dark matter particles interacting with its detectors.

The controversy

The controversy arises from the interpretation of the DAMA result as WIMP dark matter: this interpretation is incompatible with many experiments in the framework of standard WIMP and astrophysical model. Uncertainties in the dark-matter model, the halo model, and the detector response itself makes extremely arduous to make a model-independent comparison between DAMA/LIBRA and other experiments with different targets. Moreover, the sheer significance of the DAMA/LIBRA signal makes its result not so easy to dismiss. To resolve this controversy, a new experiment based on NaI(Tl) crystals is needed: the SABRE experiment sets its main goal on finding a solution for this controversy.
2.1. The DAMA/LIBRA experiment

(a) DAMA/LIBRA modulation amplitude $S_m$ as a function of energy

(b) The energy spectrum of single-hits events in DAMA/LIBRA

Figure 2.8: DAMA/LIBRA modulation amplitude and single-hit event rate
2.2 The SABRE experiment: Sodium-iodide with Active Background REjection

An independent test of DAMA/LIBRA by using the same target is strongly desired by the scientific community. However, the sheer significance of the DAMA result and the high-purity achieved for its apparatus, make the DAMA/LIBRA claim not easy to verify. The longstanding result asks for such a test to be enough robust to support it or to rule it out. The new experiment, therefore, must be not only a replication of DAMA/LIBRA, but also an improvement in order to become a strong, direct-detection experiment by itself. SABRE (Sodium-iodide with Active Background REjection) is a new NaI(Tl) experiment seeking to provide the above-mentioned test on the DAMA/LIBRA claim. It uses a multi-stage approach to improve upon DAMA/LIBRA, consisting in lowering the background and the energy threshold, using active background rejection system and operating in different sites. The SABRE experiment will consist in developing twin detectors of NaI(Tl) crystals in arrays, immersed in liquid scintillator acting as an active veto, located in two different sites in the opposite hemispheres: at the Gran Sasso National Laboratories (LNGS) in Italy, and in the Stawell Underground Physics Laboratory (SUPL) in Australia.

The full SABRE project will be forerun by SABRE Proof-of-Principle (PoP), intended to be a phase where the crystals are developed and tested in the liquid active veto. The aim of SABRE PoP is to achieve an overall background at least 10 times lower than DAMA/LIBRA one, in the energy region where DAMA/LIBRA sees the annual modulation, i.e. 2-6 keV$_{ee}$. SABRE PoP is going to be built and operated in the LNGS site.

2.2.1 Overview of the SABRE experiment

As previously said, the SABRE experiment will consist of an array of NaI(Tl) ultra-pure crystals, each coupled to two low-background, high-quantum efficiency photomultiplier tubes. The crystals will be wrapped in a reflector to prevent the escaping of scintillation light and enhance the light collection efficiency. The crystal and the two PMTs will be encased in a copper enclosure and immersed into a liquid scintillator, contained by a vessel. All around the vessel, layers of passive shielding will provide, together with the underground location, a shield against environmental and cosmic backgrounds.

2.2.2 SABRE requirements: the four pillars

SABRE has four main cornerstones which, if achieved, will guarantee the result: lowering the backgrounds with ultra-pure crystals, the use of an active background-rejection veto, using a double sites in the northern and in the southern hemispheres, and lowering the energy threshold with high Quantum Efficiency PMTs.

Ultra-high radiopure crystals

The first, fundamental goal is to achieve and improve, in terms of radioactivity, the DAMA/LIBRA quality of the crystals. The production of DAMA crystals at Saint Gobain
2.2. The SABRE experiment

has long been discontinued and cannot be reactivated. It is therefore necessary for SABRE to develop new high-pure crystals, able to reach and improve the radiopurity respect to the DAMA ones.

The purity of the crystals depends both on the purity of the powder used and in the growing methods. SABRE partnered two company, the Sigma Aldrich SAHC HiTech and the Seastar Chemicals Inc./MV Laboratories Inc., to develop the crystal powders and test their radiopurity. While the Sigma Aldrich made a partnership with the Princeton University in order to develop and upgrade methods and purification techniques, the Seastar focused on the development of the technique used for measuring very low concentrations of impurities, in particular $^{nat}K$, such as the Inductively Coupled Plasma Mass Spectroscopy (ICP-MS); they have also developed their own highly-pure powders. Tests on the $^{232}$Th and $^{238}$U concentrations in powders and crystals have been made thanks to the partnership of Princeton and the Pacific Northwest National Laboratory (PNNL).

The crystal growth has been commissioned to the Radiation Monitoring Devices (RMD) Inc., a company specialised in purification methods and crystal growth in detector applications. The aim is to achieve an unprecedented radiopurity.

In the growth of NaI(Tl) crystals, several considerations need to be taken into account during the process. The highly hygroscopic nature of the NaI, for example, complicates the procedure: as a matter of fact, when NaI is exposed to moisture, its optical properties degrade in a significant way, yellowing the crystal and making it weaker, introducing cracks and cloudiness. The cracks occur mostly when it sticks to the container in which it is grown. During the growing process, it is therefore needed to consider the physical integrity of the crystal, in all the parts of the growth.

Before, during and after the growth a particular attention should be paid on powder exposure and the crystal to external contaminations. All the materials and the atmosphere where the powder and the crystal are kept must be as free as possible from contaminations (the radon in the atmosphere, for example).

The Kyropoulos method, used by DAMA/LIBRA, is not the only one that can be used for the crystal growth, even if it is considered one of the purest process. SABRE, instead, has primarily pursued the Vertical Bridgman (VB) [33] method of growth for its crystals. In the VB method, there is an ampoule, that is a long, sealed container typically made of quartz, containing the material. Because NaI(Tl) can stick to this material, an open container shaped like a long cup, called "crucible", may be used as an internal container to hold the powder. The crucible is in turn sealed in the ampoule after being packed with powder and pumped down to vacuum. The material is melted from the bottom of the crucible, and the crucible is slowly lowered out of the heating element so that the crystal is formed from the bottom up. Impurities are pushed up the volume during the formation of the crystal. Crystals grown by the VB method can be then sectioned after growth, removing the most impure section at the top, and regrown again. This multiple-growth method can be used as an additional purification step.

The VB method has several advantages compared to the Kyropoulos method. Surely, the main one is that in the Kyropoulos the container of the powder is open to the atmosphere
2.2. The SABRE experiment

inside the furnace, which has an unknown cleanliness. Moreover, the VB method has no limit on the crystal size: the diameter can be limited by the crucible size, while the length is not. For the Kyropoulos method, the RMD has more difficulties on developing a large system, whereas in the VB method they have a long experience. Finally, even though the Kyropoulos method does not give any chance to the crucible’s walls to touch the crystals, this effect can be mitigated by choosing, for the VB method, crucibles built with high-purity materials.

Small crucibles and ampoules were fabricated from different high-purity materials in order to test for leaching effects. In addition, these tests would also serve to test whether crystals would stick to these different materials and crack after growth. SABRE further purified the materials used in the crucibles and ampoules for this test through special cleaning procedures. Small crystals were grown with them; the crystal material was measured for radioactivity, along with a sample of the NaI powder for reference. This was done to test whether impurities were added to the crystal during the growth process, and whether the addition of impurities might be attributable to the crucible or ampoule material. Another measurement was made on a normal-purity NaI(Tl) crystal grown by the Kyropoulos method at RMD’s sister company, Hilger Crystals. More details on crystal growth can be found in [44]

Figure 2.9: The small crystal growth with the VB method

In addition to possible contamination from the crucible/ampoule materials themselves, it is possible that contamination may occur in the preparation and growth stage from other sources, such as the handling of the materials, the baking of parts, or the packing of the raw material. So other tests have been performed in order to understand the importance of these kind of contributions. 

The results of the main radioactive backgrounds from these small crystals are presented in
2.2. The SABRE experiment

Table 2.1, compared with the DAMA/LIBRA ones.

<table>
<thead>
<tr>
<th>Element</th>
<th>DAMA/LIBRA [ppb]</th>
<th>SABRE [ppb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{39}$K</td>
<td>13</td>
<td>9</td>
</tr>
<tr>
<td>Rb</td>
<td>&lt;0.35</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>U</td>
<td>$0.5-7.5 \times 10^{-3}$</td>
<td>$0.6 \times 10^{-3}$</td>
</tr>
<tr>
<td>Th</td>
<td>$0.7-10 \times 10^{-3}$</td>
<td>$0.5 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

Table 2.1: One SABRE 2-kg test crystal compared to DAMA/LIBRA [26]

The test crystal shows a K concentration of $\sim 9$ ppb, below the average value of DAMA. This is a breakthrough in crystal development, after several years of world wide efforts during which the background level of DAMA crystals has remained unmatched. The concentration of $^{87}$Rb is below the detection limit of 0.1 ppb (DAMA upper limit: 0.35 ppb). The first full size crystal (>5 kg) is currently under growth, and will be tested in 2017 in the Proof-of-Principle detector further described.

Active veto

As mentioned before, the $^{40}$K decaying in Ar is one of the most dangerous backgrounds for DAMA/LIBRA, because of the 3 keV$_{ee}$ electron or X-ray emitted. The SABRE approach is to use a feature of this decay, detecting the $\gamma$ emitted at 1461 keV with a liquid scintillator all around the detectors. With this technique, lower backgrounds than those of DAMA/LIBRA may be achievable. Passive shielding is armless against the internal backgrounds caused by radioactive decays happening in the detectors themselves. By surrounding the detector materials with a liquid-scintillator vessel, with photomultipliers detecting the scintillation light, particles that deposit energy in the main detector and then escape can be tagged on the way out (see Figure 2.10). $^{40}$K decaying by electron capture to $^{40}$Ar triggers a cascade that includes K- and L-shell X-rays or Auger electrons, some with an energy of about 3 keV. One of the main purposes of deploying the crystals in an active veto detector is the rejection of low-energy, internal $^{40}$K backgrounds by a detection of the 1461 keV $\gamma$ ray as it escapes the crystal volume. Surrounding the detector with a liquid scintillator could guarantee a $4\pi \gamma$ detection with about 80% efficiency on suppression of these kind of backgrounds, according to Monte Carlo simulations.

Not only the $^{40}$K is a background that can be rejected with the active veto: cosmogenics and radiogenics can produce sources of backgrounds depositing a small amount of energy as they pass through the detectors. For example, $^{22}$Na emits with a branching ratio of $\sim 10\%$ a 0.8 keV X-ray together with a 1275 keV $\gamma$. This is particularly relevant as SABRE’s aim is to achieve a threshold below 2 keV. In Figure 2.11 it is possible to see the efficiency of the veto against the backgrounds, while in 2.12 the DAMA rate compared to the SABRE
2.2. The SABRE experiment

Figure 2.10: The active veto concept

awaited one with the active background rejection.

The active veto has no possibility to tag those events that are completely confined inside the crystal; particularly dangerous are the pure \( \beta \) decays with a low Q-value, such as \(^3\text{H}\), \(^{87}\text{Rb}\) and \(^{210}\text{Pb}\). This fact enforces the requirement of ultra-pure crystals.

Double site experiment

An annual modulation arising from dark matter will have the same phase regardless of the location on Earth. Seasonal effects, however, are opposite in the northern and southern hemispheres. In Australia, for example, the peak of a dark matter signal that is consistent with the DAMA result will occur six months out of phase from the maximum in muon flux and directly induced cosmogenic background. Such a location allows to better disentangle signals arising from seasonal effects from astrophysical ones. For this reason, a double site experiment has been thought: to locate one experiment in the northern hemisphere, in the same underground laboratory where DAMA/LIBRA is set, and to compare the results with data obtained from a twin detector in the southern hemisphere, provides to examine seasonal and local environmental aspects more thoroughly.

The location chosen for the southern hemisphere detector is a gold mine in Australia, the Stawell Gold Mine, near Victoria (Figure 2.13). The Stawell Underground Physics Laboratory[34] (SUPL) will take place in the disused parts of the mine (see Figure 2.14b), 1 km underground, providing at least 2900 meter water equivalent shielding against cosmic rays. The muon is similar to the average depth of Gran Sasso National Laboratory (Figure 2.14a), so the muon flux is compatible between the two sites, but with opposite phase. Once completed, at the end of 2017, it will be the first deep underground laboratory of the southern hemisphere. It will not only host SABRE, but also other dark matter experi-

\(^{210}\text{Pb}\) decay is associated to a vetable \( \gamma \) only at 4% of probability.
2.2. The SABRE experiment

Figure 2.11: Backgrounds with and without the veto in SABRE simulations using a $^{40}\text{K}$ content of 13 ppb, such as in DAMA crystals.

Figure 2.12: Comparison between the DAMA result on single-hit events, and the expected SABRE background with MC simulations ($^{40}\text{K}$ content of 9 ppb). The solid red line is positioned in the 2-6 keV region of the detected modulation signal, and its vertical position is the awaited amplitude for the annual modulation.
2.2. The SABRE experiment

ments, such as CYGNUS 1.1 [38].

![Figure 2.13: The location of the two twin detectors, for SABRE North and SABRE South](image)

![Figure 2.14: Representation of the LNGS and SUPL laboratories](image)

**Low energy threshold**

The energy range where DAMA/LIBRA sees its modulation is very close to their software threshold (set to 2 keV) and a region heavily populated by electronic noise events. DAMA attributes these noise events to fast single photoelectrons in the PMTs [35]. One way to become more sensitive to the presence of WIMPs and a modulation signal would be to lower
the energy threshold of the experiment, because the rate of scattering increase. Lowering
the energy threshold is also advantageous because of the signature of the WIMP modu-
lation. The modulation phase reverses at low energies, and the location of this reversal
depends on the WIMP mass [36], as it can be seen in Figure 2.15. If one interprets the
DAMA results in term of scattering of WIMP, two possible solutions can be depicted, as
said before: a 80-GeV WIMP interacting with the iodine, or a 10-GeV WIMP interacting
with sodium. The phase reversal happens, just below the DAMA energy threshold of 2
keV, in the 80-GeV WIMP, while for the light-WIMP the modulation continues to increase
at lower energies. Lowering the energy threshold could help distinguish between the two
DAMA regions of interest, if confirmed.

![Figure 2.15: Modulation amplitude from DAMA results vs. the expected behaviour for
an 80-GeV WIMP (dotted black line) and a 10-GeV WIMP with different quenching factor
(solid red and dashed blue lines)](image)

It is of fundamental importance to lower the energy threshold, and there are several
ways to do it and to improve the signal collection. The first method is to reduce that noise
that can obscure legitimate low-energy scintillation signals. This can be done by noise-
rejection techniques or by operating the PMTs in a low-noise configuration. The second
is to increase the detector response for a given energy by increasing the light yield of the
detectors and the light collection efficiency.
Both of these methods, anyway, are strictly connected to the performance of the PMTs:
the low-noise configuration of the PMTs implies a low dark rate contribute, while the light
yield is related to the quantum efficiency. SABRE will start with the Hamamatsu R11065-
20 model, a 3" device developed for low background experiment such as DarkSide [37].
These PMTs are expected to have a radioactive contamination lower than 10 mBq/PMT,
so they will be coupled directly to the crystal surface without the use of light guides as
for the DAMA experiments, improving the light collection efficiency. The background
contribution from the single PMT has been simulated with the Geant4 toolkit (version
10.2. The radioactivity values used were those that had been measured for the Xenon R11410-21 PMTs [40] [41]. These PMTs are identical to the R11065-20 PMTs that will be used by SABRE, except for their photocathode material. The PMT window\(^3\), the PMT body, and the feedthroughs are the dominant sources of backgrounds for the PMTs. These parts have been simulated independently. The electrodes and other internal components of the PMT have not been simulated. The total background contribution from one PMT in the 2-6 keV range amounts to less than \(\sim 4 \times 10^{-3}\) cpd/keV/kg (upper limit with veto ON), as can be seen in Figure 2.16. This value has to be compared with the crystal intrinsic background contribution which is of the order of \(1.5 \times 10^{-1}\) cpd/keV/kg, and with the total background budget (including crystal intrinsic background, crystal wrapping, crystal PMTs, crystal enclosure, liquid scintillator and steel vessel) which is of the order of \(1.6 \times 10^{-1}\) cpd/keV/kg (upper limit with veto ON). Comparing Figure 2.16 to Figure 2.12, it can be seen that the PMTs background contribution is a factor of 20 lower than the total background of SABRE. This provides some comfort in the estimation of the contribution of the PMTs in the background measurements.

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{background_plot.png}
\caption{Upper and lower limit of the total background due to a single PMT (see Section 3. It includes background profile both with veto ON and OFF.)}
\end{figure}

The PMTs are planned to operate below the nominal gain, in order to reduce the emission of afterglow light which can travel back to the crystal and be seen by the opposite PMT, resulting in coincident signals that would match the trigger condition. The compensation for the reduced gain will be done with low noise custom preamplifiers mounted on the back of the PMTs. Moreover, there is a cooperation with Hamamatsu in order to build new devices improved for the needs of the experiment. A first aim could be the replacement of the ceramic stem with individual ceramic pin feedthroughs which would lower the light emission from ceramics and further reduce the radioactive background. A

\(^3\)The evaluation of the PMT window as a background source includes contributions by the photocathode as well as by the fused silica.
second aim could be to replace the photocathode, designed for low temperature operation, with a super-bialkali photocathode for a slightly higher quantum efficiency and much lower dark noise at room temperature.

2.2.3 Competitors

The claim of DAMA/LIBRA has caused a global effort for searching a confirmation during these years. SABRE is not the only nor the first experiment in trying to do so: a brief list of the competitor experiments and the relative state-of-art is described below.

ANAIS

ANAIS (Annual modulation with NAI Scintillators) is an experiment at the Canfranc Underground Laboratory (LSC), located in Spain, 2450 mwe deep. Its aim is to confirm the DAMA/LIBRA modulation signal using the same target and technique, but with a change of location and with a different experimental approach. After several steps, ANAIS is currently in the ANAIS-112 phase, in which a 3x3 matrix of 12.5 kg cylindrical modules of NaI crystals forms a 112 kg of active mass detector. The main problem this detector has is to handle the unsatisfactory radiopurity of its crystals, due to a massive presence of $^{210}\text{Pb}$, and a potassium content of 20 ppb against the 13 ppb content of the DAMA ones. A liquid scintillator (LAB) veto can be incorporated in a second phase of the experiment [45].

KIMS

The Korea Invisible Mass Search experiment (KIMS), located at the Yangyang underground laboratory (2000 mwe), in Korea, began its approach to the dark matter search using an array of 12 low-background CsI crystals for a total mass of 104.4 kg. Thanks to the 2.5-year of data taking with with a 2-3 counts/kg/day/keV background, they can state a rejection of the interpretation of the DAMA/LIBRA signals as WIMP-iodine interaction. With this experience, the KIMS experiment has begun to develop a NaI crystal array in order to try to analyze the same annual modulation as the DAMA one, further stating a partnership with the DM-Ice group for the COSINE experiment [27] [31].

DM-Ice

DM-Ice is another NaI(Tl) direct detection dark matter experiment. DM-Ice is a phased experimental program: the first generation, DM-Ice17, deployed 17 kg of NaI(Tl) into the South Pole ice, at 2450 depth (that is 2200 mwe). This is the first, unique dark matter experiment using crystals running in the southern hemisphere. DM-Ice37 with 37 kg of NaI(Tl) is in on-going R&D status at Boulby Underground Laboratory, in the United Kingdom. Because of the unsatisfactory results in the crystals radiopurity, DM-Ice and KIMS are working together to form the COSINE experiment [31], commissioning a 100-kg of NaI detectors deployed in Yangyang Laboratory [46].
2.2. The SABRE experiment

COSINE

COSINE-100 is a NaI(Tl) experiment born from a collaboration between the DM-Ice and KIMS experiments. The first phase of the experiment deployed 106 kg of NaI(Tl) at Yangyang underground laboratory in South Korea, and started to take physics data in September 2016. It consists in a 8-crystals array with total mass of $\sim 100$ kg, surrounded by 2000 L of LAB liquid scintillator filled inside a copper box, with a passive shielding of lead. All around, plastic scintillators have the purpose to tag muon events from cosmic rays.

According to their studies ([32]), COSINE-100 has the capability to directly test DAMA’s results within a time period of $\sim 2$ years.

COSINUS

At the LNGS, a new R&D project for a NaI experiment named COSINUS (Cryogenic Observatory for SIgnatures seen in Next-generation Underground Searches) aims to develop a cryogenic scintillating calorimeter using an undoped NaI-crystal as target for direct dark matter search. Dark matter particles interacting with the detector material can generate both a phonon signal and scintillation light. The particle identification is allowed thanks to the measured scintillation light, while the phonon signal provides a determination of the deposited energy. Using the same target material as the DAMA/LIBRA collaboration, the COSINUS technique may offer a good possibility to investigate and contribute information to the presently controversial situation in the dark matter sector [39].

2.2.4 SABRE Proof-of-Principle

The SABRE experiment is currently in a Proof-of-Principle (PoP) phase with a double goal: demonstrating the production of radiopure crystals and reaching a sufficiently low and well known background to carry out a test of the DAMA/LIBRA claim for a dark matter signal.

During this phase, one 5-kg radio-pure crystal will operate in an environment similar to the full-scale experiment, inside a veto vessel consisting of a cylindrical, steel tank 1.52 m long and 1.37 m in diameter sitting on its rounded side. The crystal detector will hang in the center from a port at the top (see Figure 2.17). Two PMTs Hamamatsu R11065-20, 3'-diameter, will be coupled to the crystal in a clean room and encased into the copper enclosure. The enclosure will be made of high purity copper and PTFE. In Figure 4.1, an illustration of the enclosure is shown.

To put the enclosure inside the veto vessel, a Crystal Insertion System (CIS) has been proposed. Two options have been explored: a “wet” insertion, meaning that the crystal enclosure is directly touched by the liquid scintillator contained by the vessel (Figure 2.19), and a “dry” insertion, where a stainless steel bar connects the enclosure with the flange, allowing the enclosure to be inserted inside a thin copper tube attached to the flange. For the initial phase has been chosen the dry solution, because it is simpler to handle if some
2.2. The SABRE experiment

Figure 2.17: The SABRE PoP vessel and detector module (wet option)

Figure 2.18: Illustration of the copper enclosure with the crystal and PMTs hosted
adjustment requires to open the vessel, while the wet one will be adopted in the future. 
The background is almost the same for the two configurations. 
The inner volume is flushed with boil-off dry N$_2$ gas through Teflon tubes running into 
the space between the copper tube and the enclosure. The flushing minimizes potential 
contamination e.g. due to radon close to the crystal enclosure. An additional Teflon tube, 
connected to the same flange, allows for the insertion of a calibration source, mounted on 
a wire. To ensure a precise insertion of the copper tube as well as the detector module a 
removable aluminum frame will be mounted atop of the vessel.

**Figure 2.19:** The thin copper tube used for the dry CIS

10 PMTs, five on each end, will be installed in ports on the flat ends of the vessel 
to collect the scintillation light. The vessel will be filled with a liquid scintillator, the 
pseudocumene (PC), with the wavelength shifter PPO. It will be lined with Lumirror 
reflector to increase the light collection. The vessel will in turn be surrounded by passive 
lead, polyethylene and water shield to keep the veto rate low.
The SABRE external shielding design can be seen in Figure 2.20. The bottom of the 
shielding is composed of 15-cm lead and 10-cm polyethylene. All around the vessels, 40-
cm thick polyethylene slabs are arranged to create walls on three sides. The polyethylene 
structure will sustain the weight of a steel plate. On the top of it, one-meter-thick water 
tanks will sit. Other water tanks will be placed outside the polyethylene walls. A fourth 
wall with exactly the same structure (polyethylene and water tanks) is designed to be 
easily removed to provide access to the vessel area. To prevent radon-rich laboratory air 
to touch the veto vessel, there is a buffer volume outside the veto vessel, created by sealing
the polyethylene box and flushed with nitrogen. The buffer volume and the inner catch basin will act as a further containment for safety.

The SABRE experiment has been assigned a location in the Hall C of the LNGS, near the Borexino storage area, but having a smaller temporary location in Hall B South for pre-commissioning and testing phase.
Chapter 3

Test of PMTs Hamamatsu 3”
R11065-20 MOD

The keystone of the SABRE experiment is inside the copper enclosure located in the vessel with the liquid scintillator: here are set the ultra-pure crystal and the two PMTs coupled to it. The choice of the PMTs for the experiment follows some features that are needed in order to reach the goal, such as a high quantum efficiency and a low dark rate. It has been made a request to Hamamatsu for a new prototype of PMT based on a model already present on the market, but with optimized characteristics for the SABRE experiment.

After a brief introduction about the operating principle of the PMTs, it will be given a list of characteristics needed for the experiment. Then, the description of the characterization of the PMTs received from Hamamatsu and the comparison with a standard one will be presented.

3.1 Photomultiplier Tubes

A PhotoMultiplier Tube (PMT) is a device that convert a light signal into current thanks to the photoelectric effect, and then amplify the signal using the multiplication effect via secondary emission. A PMT consists (see Figure 3.1) in a vacuum tube with an input window, a photocathode with a sensitive layer, focusing electrodes, several dynodes (electron multipliers) and an anode. The conversion of light into electrons begins when a photon (or more) passes through the window and impinges on the photocathode sensitive layer. This photon with frequency $\nu$, scatters against the photocathode, that has an extraction potential $\phi$ that depends on the material. Thus, the material emits an electron with energy:

$$E_{\text{electron}} = h\nu - \phi$$

The materials chosen for the photocathode facilitate the photoelectric conversion. The electrons emitted from this are called photoelectrons. The window material is also chosen in order to have an optimal matching with the spectrum of the incident light: quartz and borosilicates are usually employed but, when radiopurity becomes an important issue, one should also consider the potassium content in the choice.
In order to make the charge larger and detectable, the photoelectrons exiting the cathode are focused on a dynode, thanks to an appropriate choice of electric field. After the focusing, the multiplication is reached thanks to the phenomenon of secondary emission, that works as the photoemission but uses the energy of the incident electron to set free some electrons in the first dynode. Secondary emission takes place in each of the dynodes of the dynodic chain, thus generating a current of electrons that are finally collected at the anode.

With a resistive voltage divider it is possible to set the voltage inside the PMT, for every dynode. It is of course necessary to maintain the vacuum inside the tube, to avoid the losses of energy of the electrons scattering against ions of gas.

There are several parameters necessary to be understood for a photomultiplier characterization:

- the spectral response shows the wavelength range to which the PMT is more sensitive. It is the ratio between detected and incident photon, as a function of the wavelength;

- the quantum efficiency is the spectral response at a certain wavelength. It is measured as the ratio between emitted photoelectrons and incident photons, and should be matched with the light coming out from the detector;

- the gain is the ratio of the number of electrons collected at the anode respect to those produced by the photocathode, and it depends on bias voltage;

- the dark current is the current in the anode not produced by photons, but that comes from processes such as thermoionic emission in the photocathode and the dynodes, or leakage current between anode and electrodes, ionization current from residual gases, noise current from cosmic rays...

- the dark counts are the rate of events generating the dark current;
3.2. SABRE requirements

- the **single electron response** (SER) is the charge spectrum of the PMT in response to a single photoelectron;

- the **afterpulses**, that are a type of dark noise, consisting in pulses that can follow a real signal pulse after a short delay period. It is called *afterglow* when there is emission of light.

There are several types of PMTs depending on the photocathode type, the geometric disposition, the number of dynodes and the window material. The material of the photocathode determines the spectral response of the photomultiplier in terms of wavelength and quantum efficiency. The type of the photocathode is selected taking into account the spectrum of the light to be detected. The type and number of dynodes will determine the gain of the PMT.

Let us analyze the SABRE requirements for the PMTs that will be coupled to the crystals.

### 3.2 SABRE requirements

The ideal PMT for the detection of DM signals in the SABRE ultra-pure crystals should fulfill the following requirements:

- **High quantum efficiency**: it is needed in order to have the maximum performance from photons to electrons conversion, that is fundamental for a low threshold experiment as SABRE will be;

- **Low dark rate**: for the same low threshold reason, it is necessary to have the minimum dark counts as possible, to minimize the triggering on false events.

- **Low background**: the crystal is extremely radiopure, and the PMTs are the closest objects to it. Thus, they must be as radiopure as possible.

All these characteristics have been found in the Hamamatsu 3” R11065-20. The Hamamatsu 3” R11065 PMT was developed in collaboration with Hamamatsu Phototonics for the DarkSide experiment for low-background, cryogenic operation. This PMT has a very low radioactivity, below $\sim 5 \text{ mBq/tube}$ [40] [41]. The low radioactivity is in part due to the use of a cobalt-free metal for the casing and the replacement of the feedthrough plate, which was previously made of synthetic alumina, with a high-purity (99.9\%) ceramic. These tubes were used as the basis for further study into improvements for the PMTs, driving to the realization of the R11065-20 MOD prototype.

This work presents the characterization of three specimen of PMT R11065-20 MOD, and the comparison of their characteristics with a standard R11065-20. From an operational point of view, this has implied not only the creation of a space that has been used for the containment of the set-up and for performing all the operations, but also an assembly of a (basic) data acquisition and the production of mechanical parts (such as the copper enclosure that will be presented in Chapter 4) *ex novo*, therefore tuning their design and
3.3. PMTs characterization and comparison

In the first part, there is the introduction of the PMTs and their characterizations. In the second part, it is presented the coupling between two PMTs, to study coincidences and afterglows.

3.3 Characterization of the PMT R11065-20 MOD and comparison with the R11065-20

It is here presented the characterization and the comparison of two Hamamatsu PMT models: the standard one, called R11065-20, and the prototype R11065-20 MOD, in which the photocathode has been modified thanks to the use of a superbialkali material. The use of superbialkali permits to have a high quantum efficiency and a low dark rate at room temperature. The window glass is made of synthetic silica in order to reduce the potassium contamination.

In Table 3.1 it is possible to see the PMTs used and their factory specifications as provided by Hamamatsu.

<table>
<thead>
<tr>
<th>Name</th>
<th>Serial Number</th>
<th>Cathode Lum. Sens. µA / lm</th>
<th>Anode Lum. Sens. A / lm</th>
<th>Dark Current nA</th>
<th>Cathode QE @420 nm %</th>
<th>Blue Sens. @peak %</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMT-1</td>
<td>ZK7942</td>
<td>98.3</td>
<td>345.0</td>
<td>1.50</td>
<td>13.20</td>
<td>31.26</td>
</tr>
<tr>
<td>PMT-2</td>
<td>ZK8033</td>
<td>102.0</td>
<td>338.0</td>
<td>6.20</td>
<td>13.50</td>
<td>31.84</td>
</tr>
<tr>
<td>PMT-3</td>
<td>ZK7724</td>
<td>124.0</td>
<td>636.0</td>
<td>1.10</td>
<td>12.90</td>
<td>32.18</td>
</tr>
<tr>
<td>PMT-4</td>
<td>ZK8351</td>
<td>110.0</td>
<td>688.0</td>
<td>11.0</td>
<td>13.90</td>
<td>32.94</td>
</tr>
</tbody>
</table>

Table 3.1: Factory specifications of the PMTs provided by Hamamatsu

The name of PMTs follows the arrival order to the LNGS. From here, it will be maintained the name given as shown in the Table, so PMT-1, PMT-2 and PMT-4 for the MOD, while PMT-3 is the standard one.

In Figure 3.2, it is shown a typical single photoelectron pulse coming from a PMT; there are some features that should be noticed.

This pulse is very fast: the entire event time lasts ~ 30 ns, and this is typical for PMTs of this size. The scintillation light coming from a scintillator detector is usually larger but, above all, slower, in the order of hundreds of ns. The pulse has a negative amplitude because the charge collected at the anode comes from electrons. Directly from waveforms similar to this, one can extract the information about the amplitude and the area of the signal.

1The model is named “MOD-MS” because the change stays in the metal bottom, while there is not the superbialkali photocathode. Thus, the reference as “standard”.

In Table 3.1 it is possible to see the PMTs used and their factory specifications as provided by Hamamatsu.
3.3. PMTs characterization and comparison

Figure 3.2: Example of a typical pulse coming from a PMT

The characterization proceeds as follow:

- it is taken the Single PhotoElectron$^2$ (SPE), thanks to which one can extract the single photoelectron peak, as a function of the voltage applied;

- from here, it can be found the peak-to-valley ratio for every voltage applied;

- from the SER spectrum one can extract the PMT gain as a function of the bias voltage applied;

- finally, a dark rate measurement is made to understand the noise inside the PMT when no light illuminates it.

The set-up used is shown below. Then, the procedure for the data taking and for the analysis is described.

3.3.1 The experimental set-up

During this first stage, the set-up consisted in:

- a single PMT with a light-tight cap;

- 2 types of voltage dividers, one for the negative voltage supply, and one for the positive (in Figure 3.3 are shown the schematics used$^3$);

$^2$For Single PhotoElectron we intend the distribution of the amplitude of the PMT pulse induced by single-electron excitation.

$^3$The resistance step for each dynode has been chosen to be 1 MΩ.
3.3. PMTs characterization and comparison

- 1 metallic cylinder CF100, used to contain and shield the PMTs from external light and electromagnetic radiation;
- 1 voltage supply NHQ 202M 2x2kV/6mA double channel;
- 1 oscilloscope Teledyne LeCroy HDO6104, with a 12-bit ADC resolution (up to 15 bits with the enhanced resolution) and 4 digital channels with 2.5 GS/s sample rate;
- 1 CAEN Quad Scaler-Preset Counter Timer, mod. 145;
- 1 CAEN 6 channels Discriminator, mod. 224;
- 1 timing unit CERN n. 2255.

Figure 3.3: Electric schemes for the voltage dividers

PMTs can be operated in positive high-voltage scheme (+HV), in which the photocathode is grounded and the signal is produced at a high positive voltage, or a negative high-voltage scheme (-HV), in which the DC voltage at the anode is at ground potential, but the photocathode is at a negative high voltage. Each scheme has its own advantages and disadvantages. In the -HV scheme, the body must be insulated very carefully from other metallic detector parts that may conduct a current, and also from each other, in order to maintain a constant high voltage on the photocathode. However, in the +HV scheme, the signal comes out with a high DC offset that must be decoupled with a decoupling capacitor circuit. Because these capacitors must have a high voltage rating, they
are generally fairly bulky and can be a source of radioactive background if located on the PMT base. Moreover, it can introduce some modification in the shape of the pulse. In Figure 3.4 it is possible to see a schematic representation of the above described set-up. For each measurement, it has been used one PMT in a dark environment, with its cap to be in a dark noise regime.

![Figure 3.4: Schematical representation of the set-up used for the PMTs characterization](image)

### 3.3.2 Measurements and data taking

To make the data acquisition of the spectra measurements, such as SPE and SER, the oscilloscope has been used. The trigger level was set between -200 and -400 µV, to permit the acquisition of both real pulses coming from photoelectrons, and electronic noise. PMTs gain have been equalized with a scan of voltage supplied, using the voltage divider for both the negative and the positive HV supply. During the data taking, it has been clear that not only the area of the signal was important, but also the pre-trigger noise area: it has been noticed that every measurement was affected by a variable offset, which interfere with the real value of the area of the signal. This noise was probably due to electromagnetic interferences from switching power supplies, because it was present even when the PMTs were turned off. To manually subtract this offset, thus, a window has been opened before the trigger, so that it contained only white noise and permitted to check the offset. Both of the windows, for noise and for signal, have been chosen of the same duration, that was 20 ns.

For the dark rate measurements, the Discriminator and the Scaler have been used. In order to have the same conditions, the PMTs have been equalized. This means that from the SER measurements one has to find at which voltage the SER peak has the same values for every PMT, while the threshold level is chosen looking at the SPE spectrum and choosing 1/3 of the peak$^4$. The result of the dark counts are in Table 3.2.

$^4$More explanation about how to find the same gain level will be given in Section 3.3.3, so as the choice of the threshold.
### 3.3. PMTs characterization and comparison

<table>
<thead>
<tr>
<th>Gain ($10^7$)</th>
<th>PMT-1 (Hz)</th>
<th>PMT-3 (Hz)</th>
<th>PMT-4 (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1 \times 10^7$</td>
<td>1666 V</td>
<td>1607 V</td>
<td>1556 V</td>
</tr>
<tr>
<td>Mean($\sigma$)</td>
<td>1518.4(1.9)</td>
<td>235.8(0.5)</td>
<td>269.9(0.6)</td>
</tr>
<tr>
<td>$7 \times 10^6$</td>
<td>1591 V</td>
<td>1534 V</td>
<td>1488 V</td>
</tr>
<tr>
<td>Mean($\sigma$)</td>
<td>1258.1(1.1)</td>
<td>211.1(1.0)</td>
<td>268.5(0.4)</td>
</tr>
<tr>
<td>$5 \times 10^6$</td>
<td>1523 V</td>
<td>1469 V</td>
<td>1425 V</td>
</tr>
<tr>
<td>Mean($\sigma$)</td>
<td>1126.2(2.0)</td>
<td>209.8(0.7)</td>
<td>283.20.6)</td>
</tr>
<tr>
<td>$3 \times 10^6$</td>
<td>1426 V</td>
<td>1374 V</td>
<td>1336 V</td>
</tr>
<tr>
<td>Mean($\sigma$)</td>
<td>878.9(1.3)</td>
<td>206.6(0.5)</td>
<td>310.5(1.0)</td>
</tr>
</tbody>
</table>

**Table 3.2:** The dark rate mean and standard deviation for each PMTs at four different gains. The threshold values are those corresponding to $1/3$ of pe for each gain.

Other measurements of dark rate have been taken. To avoid systematic effects due to the varying of external parameters, it has been done a study of the dark rate as a function of temperature, and a measurement of the dark rate as a function of time after light exposure. The behaviour of the dark rate after a light exposure helps to study the time at which the dark counts become stable again.

To vary the temperature slowly, an air-conditioning system and a heater have been used. Inside the cylinder, it has been put a temperature-sensor, connected to a wire to the external environment and with a digital reading system, which permitted to read the temperature inside the cylinder. The precision of the sensor was $0.1^\circ C$. In Figure 3.5, it is possible to see the plot drawn from data taken, as a function of temperature. The rise of the temperature of $1^\circ C$ causes a dark rate rise of $\sim 4.5\%$.

Then, a study of the dark rate after some seconds of light exposure has been made. The light cap has been put off for some seconds, in a not dark environment and without voltage supplied, and then put on again. To calculate the time after this light exposure, the first 450 s have been devoted to gradually increase the bias voltage applied to the PMT. When the voltage supply reached the nominal gain, the time has been set to zero and then the dark rate has been taken every 100 s. In Figure 3.6 it is possible to see the expected exponential decay behaviour\(^5\) of the dark count as a function of time after light exposure, from the time when the gain level has been reached. The function used to fit the data has been:

\[
f(x) = a_1 e^{-\frac{x}{b_1}} + a_2 e^{-\frac{x}{b_2}} + c\tag{3.2}
\]

being $a_1 = 265.5 \pm 11.8$ c/s, $b_1 = 8.65 \pm 0.3$ s, $a_2 = 752.6 \pm 13.2$ c/s, $b_2 = 1.53 \pm 0.1$ s and $c = 214.9 \pm 0.7$ c/s.

\(^5\)Actually, there are two exponential regimes, one fast and one slow.
3.3. PMTs characterization and comparison

![Figure 3.5: Study of the dark rate dependence on temperature](image1)

Figure 3.5: Study of the dark rate dependence on temperature

![Figure 3.6: Dark rate as a function of time after light exposure in linear-logarithmic scale. The asymptotic value $c$ has been subtracted](image2)

Figure 3.6: Dark rate as a function of time after light exposure in linear-logarithmic scale. The asymptotic value $c$ has been subtracted
3.3.3 Data analysis

Three data sets have been obtained from the data taken with oscilloscope: the distribution of the signal peak in amplitude, the distribution of the area of the pulses, and the distribution in area of the pre-trigger noise. From the amplitude measures it has been possible to make a fit to extract the SPE peak values and the peak-to-valley ratio, for each voltage applied, while from the area measurements the PMT gain can be calculate. For plotting and fitting the data, the *gnuplot* program has been used.

- **Amplitude measurements: Single PhotoElectron peak and Peak-to-Valley ratio**

  As it can be seen from Figure 3.7, the amplitude spectrum of the single photoelectron has two parts very well recognisable. The main part of the spectrum is the single photoelectron peak, that follows a gaussian distribution, while the electronic noise part is the one with smaller area, following an approximate exponential curve. The peak value extraction has been done with a gaussian fit of the signal, followed by an exponential fit of the electronic noise part and, finally, the sum of them. In this way, it has been possible to obtain the value of the local minimum presents between SPE peak and exponential part, and to make the ratio between peak and this “valley”. It is thanks to the presence of this minimum that it is possible to discriminate between signal and noise: the higher the peak-to-valley ratio (P/V), the more one can discriminate. From this value it is also possible to understand if the voltage applied to the PMT is enough to distinguish signals from noise. The minimum is also helpful in the definition of the threshold for subsequent measurements: as a matter of fact, it corresponds at about 1/3 of the SPE peak, so choosing this value as threshold can guarantee a good discrimination between single photoelectron and electronic noise. The variation of the baseline has the effect of varying the signal amplitude, but it does not affect in a fundamental way the choice of the threshold.

  In Tables 3.3 and 3.4, the SPE and P/V measurements have been reported, for each PMT at every voltage applied.

  From these Tables results clear that the voltage divider for the negative voltage supply has the best values in terms of P/V. Moreover, in the voltage divider for the positive HV supply it is present the decoupling capacitor which influences the output of the signal, provoking a distortion of it. It is for these reasons that in the next measurements only the voltage dividers for negative HV supply have been used.

- **Area measurements: SER peak value and gain**

  With the area measurements it is possible to extract the gain as a function of the voltage applied. This can be done with the formula:

  \[
  G = \frac{Q_{\text{tot}}}{e} = \frac{\int_{t_0}^{t_1} V(t)dt}{eR} \tag{3.3}
  \]

  that permits to obtain the gain G through the ratio of the total charge Q and the single electron charge e, being Q the time integral of the signal amplitude, divided
3.3. PMTs characterization and comparison

Figure 3.7: Total fit of the data from the amplitude measurements for PMT-1 at -1700 V. In red, the data taken; in purple, the Single Electron peak, while in light blue and in green two decreasing exponential functions. The total fit is the solid blue line.

Table 3.3: Scan at different voltages for PMT-1, PMT-3 and PMT-4, with voltage divider for negative (-HV) supply. It is also written the value of the SPE peak value in mV, and the P/V value.
3.3. PMTs characterization and comparison

Table 3.4: Scan at different voltages for PMT-1, PMT-3 and PMT-4, with voltage divider for positive (+HV) supply. It is also written the value of the SPE peak value in mV, and the P/V value

<table>
<thead>
<tr>
<th>Voltage V</th>
<th>SPE mV</th>
<th>P/V</th>
<th>Voltage V</th>
<th>SPE mV</th>
<th>P/V</th>
<th>Voltage mV</th>
<th>SPE</th>
<th>P/V</th>
</tr>
</thead>
<tbody>
<tr>
<td>+1400</td>
<td>-1.369 ± 0.022 1.1</td>
<td></td>
<td>+1300</td>
<td>-</td>
<td>-</td>
<td>+1300</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>+1440</td>
<td>-1.682 ± 0.012 1.4</td>
<td></td>
<td>+1340</td>
<td>-1.227 ± 0.037 &lt;1</td>
<td></td>
<td>+1350</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>+1480</td>
<td>-2.153 ± 0.015 1.9</td>
<td></td>
<td>+1380</td>
<td>-1.567 ± 0.011 1.4</td>
<td>+1400</td>
<td>-1.962 ± 0.008 3.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>+1520</td>
<td>-2.708 ± 0.012 1.8</td>
<td></td>
<td>+1420</td>
<td>-1.915 ± 0.007 2.3</td>
<td>+1420</td>
<td>-2.241 ± 0.007 4.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>+1560</td>
<td>-3.232 ± 0.020 2.2</td>
<td></td>
<td>+1460</td>
<td>-2.393 ± 0.007 2.9</td>
<td>+1440</td>
<td>-2.725 ± 0.013 4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>+1600</td>
<td>-4.284 ± 0.016 1.9</td>
<td></td>
<td>+1500</td>
<td>-3.055 ± 0.009 3.4</td>
<td>+1460</td>
<td>-3.081 ± 0.008 4.3</td>
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<td></td>
</tr>
<tr>
<td>+1620</td>
<td>-4.653 ± 0.038 2.2</td>
<td></td>
<td>+1520</td>
<td>-3.402 ± 0.011 3.8</td>
<td>+1480</td>
<td>-3.445 ± 0.008 4.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>+1640</td>
<td>-5.154 ± 0.018 1.9</td>
<td></td>
<td>+1540</td>
<td>-3.794 ± 0.015 3.8</td>
<td>+1500</td>
<td>-3.863 ± 0.016 4.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>+1660</td>
<td>-5.715 ± 0.021 1.9</td>
<td></td>
<td>+1560</td>
<td>-4.225 ± 0.008 3.4</td>
<td>+1520</td>
<td>-4.292 ± 0.013 4.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>+1680</td>
<td>-6.248 ± 0.044 2.2</td>
<td></td>
<td>+1580</td>
<td>-4.737 ± 0.013 3.6</td>
<td>+1540</td>
<td>-4.769 ± 0.010 5.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>+1700</td>
<td>-6.834 ± 0.040 1.9</td>
<td></td>
<td>+1600</td>
<td>-5.235 ± 0.010 3.4</td>
<td>+1560</td>
<td>-5.312 ± 0.011 4.4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

by the circuit resistance R. Thus, the area measure permits to extract the gain as a function of the voltage applied and to make a fit to evaluate the linearity of it.

Even to extract the SER peak value from data it is needed a fit with a gaussian distribution. In this case, however, it is necessary to take into account the eventual offset contained in the data (which can change the area up to 10%). To avoid that this affect the signal area, the pre-trigger area has been subtracted from it. In Figure 3.8, for example, one can see the data referring to the PMT-3 at -1500 V.

In Table 3.5 it is possible to see the values resulting from the fit, for the three PMTs at different voltages applied, with the use of the voltage divider for negative HV supply. The value of the baseline has already been subtracted from the SER peak.

Having the SER values of the peak, it is possible to extract the gain as a function of the voltage applied (Figure 3.9). From data, one can infer that the gain is a monotonically increasing function of the voltage applied, following the power law given by:

\[ G = A \cdot V^B \]  \hspace{1cm} (3.4)

From the fit, it is possible to derive the gain function parameters and the G-V characteristics. In Table 3.6 it can be seen the parameters from the fit: it has been used the logarithm for the A parameter because it is possible to use the logG-logV law in order to visualize the linearity.

To choose the working gain, one can do some measurements in conditions of nominal gain, that is \( 5 \times 10^6 \) as suggest from Hamamatsu, or under this value (for example \( 3 \times 10^6 \)). Or one can choose also to be in a condition of gain higher than the
3.3. PMTs characterization and comparison

![Histogram of PMT measurements](image)

**Figure 3.8:** Measurements in area referring to PMT-3 at -1500 V. In red, the area obtained from the signal window, while in blue the one from the pre-trigger window.

**Table 3.5:** Scan at different voltages for PMT-1, PMT-3 and PMT-4, with negative voltage divider (-HV). It is also written the value of the SER peak value in pVs (the baseline has already been subtracted).
3.3. PMTs characterization and comparison

<table>
<thead>
<tr>
<th></th>
<th>PMT-1</th>
<th>PMT-3</th>
<th>PMT-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>logA</td>
<td>-17.89</td>
<td>-17.54</td>
<td>-18.29</td>
</tr>
<tr>
<td>B</td>
<td>7.63</td>
<td>7.69</td>
<td>7.92</td>
</tr>
</tbody>
</table>

Table 3.6: Parameters from the gain function

Figure 3.9: Comparison of the PMTs gain. The green points are the values voltage-gain of PMT-1, the blue ones are for PMT-3, while in red the PMT-4 values. The fit is represented by the solid line.
nominal one, such as $7 \times 10^6$ or $1 \times 10^7$. All these possibilities are displayed in Table 3.7, where it is also shown the SER peak values obtained from these gains. To choose the threshold for the Discriminator, it is necessary to take the SPE peak value corresponding to the voltage as close as possible to the gain chosen. For example, for PMT-1 at gain $1 \times 10^7$, it has been taken the SPE peak value corresponding to the voltage -1660 V.

<table>
<thead>
<tr>
<th>Gain</th>
<th>PMT-1</th>
<th>PMT-3</th>
<th>PMT-4</th>
<th>SER</th>
<th>SPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1 \times 10^7$</td>
<td>-1666</td>
<td>-1607</td>
<td>-1556</td>
<td>-40</td>
<td>-7.20</td>
</tr>
<tr>
<td>$7 \times 10^6$</td>
<td>-1591</td>
<td>-1534</td>
<td>-1488</td>
<td>-28</td>
<td>-5.10</td>
</tr>
<tr>
<td>$5 \times 10^6$</td>
<td>-1523</td>
<td>-1469</td>
<td>-1425</td>
<td>-20</td>
<td>-3.38</td>
</tr>
<tr>
<td>$3 \times 10^6$</td>
<td>-1426</td>
<td>-1374</td>
<td>-1336</td>
<td>-12</td>
<td>-2.01</td>
</tr>
</tbody>
</table>

Table 3.7: Value of the gain and of the extracted SER peak, the SPE peak value and the voltages for all PMTs needed to reach the corresponding gain

Finally, it is possible to think about the nature of the errors presented in Table 3.5. The uncertainty is purely statistical, and derives from the data fit. Thus it is useful to analyse, from Equation 3.3, the terms that are taken into account in the gain calculation.

The circuit resistance is not precisely measurable; its range of relative error is in the order of 1%. So it is a systematic source of uncertainty on the data, but it can be ignored because all the data are affected from it in the same way. It can be put as a constant.

The voltage applied, on the contrary, can be affected by both statistical or systematic errors. During the data taking, the digital value of the voltage supply varied of 1 or 2 V. This can be caused by a not constant voltage supplied or to a sensor not enough precise. The contribution of the pure statistical error is calculated by the fit, while the systematic can be evaluated as a 2 V effect on the PMT gain.

Making the derivative of the gain function $G$, one finds:

$$\frac{dG}{dV} = A \cdot B \cdot V^{B-1}$$

The uncertainties of the gain results to be in a range of 0.5-0.6%. This has to be added to the statistical error in Table 3.6.

### 3.3.4 Multiphoton measurements

A study of the PMT responses to a controlled light source illumination permitted to obtain a multiphoton electron spectrum. In order to make this measure, the set-up has gone under some changes.

- The PMT under measurement had no tight light cap, and only the negative voltage divider has been used.
The controlled light source was a pulsed laser EPL-445 from Edinburgh Instruments.

- 1 ND filter with optical density $\simeq 5$ has been put on the laser output window.

- 1 Hewlett-Packard 6632A System DC was the power supply for the laser.

The laser had a time pulse of around 100 ps. It has been possible to choose and fix the repetition rate of the laser light at 50 $\mu$s. A filter has been placed on the output window light of the laser, in order to have a small amount of photons. One of the two flanges of the cylinder has been modified: it has been made a hole in which to place the laser and point directly to the photocathode. In Figure 3.10 it is shown the flange with the laser mounted.

![Figure 3.10: The pulsed laser used for the measurements and the flange in which it has been located](image)

The data taken have been plotted and fitted with these adaptations:

- the baseline needs to be subtracted from the area of each peak. Assuming it as white noise, a gaussian distribution has been used for the fitting:

$$f_b(x) = b_b \cdot e^{\left(\frac{x-a_b}{\sqrt{2}}\right)^2}$$  \hspace{1cm} (3.6)

Finding the mean value of this gaussian\(^6\), one sets the value of the baseline;

- signals have been fitted with sum of gaussians. It is necessary to fit the gaussians increasing time to time the number of photoelectrons considered. The functions used are similar to the 3.6:

$$f_i(x) = b_i \cdot e^{\left(\frac{(x-i\cdot a-a_b)}{\sqrt{i}}\right)^2}$$  \hspace{1cm} (3.7)

Here, however, one introduces some more terms. The subscript $i$ indicates the number referring to the $i$-th photoelectrons, while the subscript $b$ refers to baseline terms. The exponential contains the subtraction of the baseline from the mean value of the gaussian. There are also two additional factors: one is related to the peak (multiplied by $i$) and one related to the standard deviation (multiplied by $\sqrt{i}$). It can be demonstrated [42] that the total fit function is a sum of gaussians in which the

\(^6\)In Figures 3.11, 3.12 and 3.13 it is not possible to see this gaussian part from the electronic noise, because data in this region are only partially displayed.
mean values and the standard deviations are strongly correlated, while the amplitude of the peaks depend only from the number of incident photons (that is, from the light source and/or from the filter), following the Poisson statistics.

With the above described methods for fitting, it is possible to obtain some spectra as the ones showed in Figure 3.11, 3.12 and 3.13.

![Figure 3.11: Multiphotoelectron spectrum and fit, for PMT-1. The blue solid line is the total multigaussian fit, while the other colored solid lines are the gaussian for the single photoelectron (green), two pe (purple), three pe (light blue), etc.](image)

The reduced chi squared resulting from these fits lay in a range between 1 and 3.6: it should be remembered that the fit has been made keeping as constant the position of the secondary peaks with respect to the first one (except for a multiplication factor), leaving as free parameters only the amplitude of the peaks. This means that the sum of gaussians used to fit the data (as presented above) are in excellent agreement with respect to the expectations. Moreover, comparing the obtained results to similar ones present in literature (for example, see Figure 3.10 in [45]), it is possible to say that the discrimination between the first and second peak is particularly good, being the peak-to-valley ratio around 1.2.
3.3. PMTs characterization and comparison

Figure 3.12: Multiphotoelectron spectrum and fit, for PMT-3. The blue solid line is the total multigaussian fit, while the other colored solid lines are the gaussian for the single photoelectron (green), two pe (purple), three pe (light blue), etc.

Figure 3.13: Multiphotoelectron spectrum and fit, for PMT-4. The blue solid line is the total multigaussian fit, while the other colored dashed lines are the gaussian for the single photoelectron (green), two pe (purple), three pe (light blue), etc.
3.4 Brief digression on the PMT ZK8033

After the presentation of the measurements on the PMTs, a brief digression on the case of the PMT model ZK8033 is needed. This PMT, renamed PMT-2 according to Table 3.1, has been sent back to the Hamamatsu after some quick tests because of an evident case of afterpulses due to lack of perfect vacuum inside the tube. Here it will be presented a summary of the tests performed. Because the flaw was quite obvious, the tests differ from the ones performed on the other tubes.

As done in the previous Sections, for PMT-2 also it has been taken the SPE and the SER spectra and performed a measure of the dark rate. In contrast with the other PMTs, however, these measurements have not been done with a scan in different voltages. This was due mainly because it has been noticed since the beginning that on the oscilloscope appeared two signals after the trigger: one was the real signal from the PMT, while the other came after 1 $\mu$s or more. Because the single photoelectron signals are small, to enhance this effect it has been chosen to couple mechanically (that is, without any optical gel) the PMT with the crystal. The scintillation light caused by the passage of particles, such as $\gamma$s from natural radioactivity or cosmic muons, through the crystal produces a larger and slower signal, more easy to see. Several waveforms at different voltages have been taken. In Figure 3.14 it can be seen three of them, taken at -800 V, -900 V and -1050 V. From these waveforms resulted very clearly the presence of the afterpulses phenomenon.

![Figure 3.14](image)

**Figure 3.14:** Waveform taken at -800 V (in blue), -900 V (in green) and -1050 V (in red). It can be clearly seen, after the main pulse happening at 0 s, the sequence of afterpulses. It is also noticeable how their position changes, increasing the voltage, becoming closer to the main signal.
To prove that those signals are afterpulses and not only random noise from the PMT, an additional measurement has been performed. Without the crystal and having the light tight cap on PMT-2, it has been done a comparison between “white” noise and the signals that followed the first pulse. Because the PMT-1 did not seem to be affected by the same problem, it has been taken from the PMT-1 a random time window signal and a pre-trigger one: these are two regions where there should be only white noise. From the PMT-2, instead, it has been taken the time window where the afterpulses appeared. Different voltages have been applied to perform this measure, changing time to time the window region in order to keep the afterpulse signal inside.

To be sure that the PMT-1 time window region are populated only by white noise, a gaussian fit of the two histograms has been made (see Figure 3.15), proving this assumption. Then, for every voltage applied at PMT-2 it has been compared the area collected in the chosen time window to the two areas taken from the PMT-1 time windows. The result can be seen in Figure 3.16.

![Figure 3.15](image)

**Figure 3.15:** Pre-trigger noise (in red) and random time window (in green) from two PMT-1, fitted with a gaussian distribution (in blue)

The conclusion after this brief analysis lead us to argue that the events following the main signal were afterpulses, due to a leak in the vacuum tube. Residual gases in the tubes are ionized by electrons, so drift back to the photocathode striking on it and provoking the release of electrons after the first signal. Because the drift time of the ions is greater than the electrons one, the delay of the afterpulses can reach few µs after the trigger.
3.4. Brief digression on the PMT ZK8033

The voltage supplied is -1200 V

The voltage supplied is -1300 V

The voltage supplied is -1400 V

Figure 3.16: The time window taken from PMT-2 in which the afterpulse event happens more frequently (in blue). Here a comparison with respect to the white noise from PMT-1 (in red) and the random time window (in green)
3.5 PMT coupling

After the characterization, the PMTs have been paired face-to-face to study some features such as the random coincidences and afterglows. Afterpulses are one type of dark noise, consisting in pulses that follow the real signal pulse after a short delay period. There are two types of afterpulses: one can rise by an emission of light from the latter stages of the multiplier structure, which can find a way back to the photocathode. The other one, is due to a non-perfect vacuum in the tube, that can give a traces of residual gas with the ionization of its atoms. The positive ions, thus, drift back to the photocathode and strike against it, releasing tens or hundreds of electrons. The differences in these two types of afterpulse lays in the time at which they appear: the first type is due to electrons that are faster than ions, so the typical delay for this pulse is 20-50 ns. The second one is due to ions, thus it can reach hundreds of ns or few µs. In these tests, the focus is set on the first type of afterpulse, in particular when there is emission of light, so they are called afterglow.

3.5.1 Experimental set-up

To study some features of the pulses above described, it is necessary to make a coupling between two PMTs, putting them face-to-face, with a minimal separation between the windows of about 1 mm. This has been done with PMT-1 and PMT-3, and with PMT-1 and PMT-4.

The set-up underwent some changes\textsuperscript{7}

- 2 PMTs facing each other;
- 2 voltage dividers for negative voltage supply;
- 1 double manual programmable Logic Unit;
- 1 National Instruments module for the DAQ.

For these tests, it has been used both the PMT-3 coupled to one PMT MOD, and the PMT-1 coupled to PMT-4. It has been chosen to perform these measurements with voltage dividers for the negative HV supply, for the reasons above-mentioned (3.3.1). In this framework, the National Instruments permits a better acquisition and a offline analysis of the signals, rather than the oscilloscope.

The PMTs coupling

In order to maintain the two PMTs firmly together, a mechanical expedient has been adopted. To have a first, elastic coupling, the two PMTs have been put closed and wrapped together with a plastic wrap and a double round of insulating tape in the border line between them. The mechanical support was constituted by a double metallic flange with four riveted metal bars, closed by nylon nuts to prevent the damage of the PMTs due to

\textsuperscript{7}When it is not specified, no changes have been done. So, for example, the Scaler has been used in the same way as before.
too much pressure. In Figure 3.17a it is possible to see the mechanical support as just described (with one metallic flange).

![Figure 3.17: The mechanical support used for the coupling](image)

Closing together the PMTs with the support (see Figure 4.2a), they have been put into the same cylinder used before.

**The electronic set-up**

The main goal of these measurements is the counting and the identification of the coincidence signals coming from the PMTs. The coincidences must not be random signals arriving at the same time, but real pulses seen from both PMTs. To recognize them and not mismatching with other kind of noise, a programmable Logic Unit has been used with the Discriminator and the Scaler. In Figure 3.18 it is possible to see a schematic picture of the used electronic set-up.

The Discriminator had a threshold of 1/3 of pe for every gain chosen, and the time window in which the signals are defined as “coincident” was of 40 ns.

The National Instruments DAQ allows the acquisition of the full waveform at high speed and reasonable resolution; the module that has been used is the PXIe-5162, a four channels 10 bit 1.25 GHz bandwidth digitizer. For these measurements, three channels have been used: one for the trigger and the others for the two PMT signals. A LabVIEW program permits to set and configure all the parameters in order to optimize the acquisition, such as the temporal length of the waveform, its resolution and dynamic range.

### 3.5.2 Measurements and Data Acquisition

It is necessary for the PMTs to work at the same gain: it has been chosen to perform the tests at four different gains, the same as in Table 3.7. The coincidences test has been done to understand if there are some differences in PMT standard versus PMTs MOD in afterglow events.

First of all, it has been done a counting of the rate of coincidences for both the set-up
3.5. PMT coupling

Figure 3.18: The electronic set-up used for the coupling

PMT-1 with PMT-3, and PMT-1 with PMT-4. The rate of random coincidences can be estimated thinking of two uncorrelated events happening in a $\tau = 40$ ns window of time:

$$R_{\text{random}} = 2\tau \cdot rate_1 \cdot rate_2$$ (3.8)

As it can be seen from the measurements of dark rate as a function of temperature, it is impossible to have a precise value for the dark rate without knowing the temperature. On average, however, it is possible to estimate the dark rate for each gain, looking at Table 3.2: here, one can say that, at Gain $7 \times 10^6$, PMT-1 has an average dark rate of 1250 Hz, PMT-3 has 210 Hz, and PMT-4 has 260 Hz (in fact, looking at the dark rate as a function of temperature, one can infer that the rate is even lower). Thus, the random coincidence rate is between the 0.02-0.03 Hz. The coincidence rate coming out from the measurements, however, is about 2 Hz, meaning that there are not only random coincidences in the event counting.

Looking at Figure 3.18, it is possible to understand the path of the signal exiting the voltage divider of each PMT. The cable goes directly into the National Instruments panel, where a T-connector splits the signal: one part goes in the acquisition, the other continues its way to the Discriminator. The high impedance (1 M$\Omega$) of the digitizer input channel avoids signal losses. Here, a first trigger is set: only signals higher than a fixed threshold are taken. Then, the signal going out from the Discriminator enters the Programmable Logic. Here, two inputs are programmed to give four output in the way shown in Table 3.8. The signals arrive in the Logic inputs, and depending on which output one chooses, the result can be the same as the first input, the same as the second, a union of the two or an intersection.

Choosing the OR output (that is, taking all the signals arriving from one PMT or from the other or from both), this can be the external trigger for the National Instruments.
3.5. PMT coupling

<table>
<thead>
<tr>
<th>$I_1$</th>
<th>$I_2$</th>
<th>$O_1$</th>
<th>$O_2$</th>
<th>$O_3$</th>
<th>$O_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>B</td>
<td>A</td>
<td>B</td>
<td>$A \cap B$</td>
<td>$A \cup B$</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
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<tr>
<td>0</td>
<td>1</td>
<td>0</td>
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<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 3.8: The logic table used in the Programmable Logic

3.5.3 Data Analysis

For the analysis of the waveforms taken with the National Instruments tool, it was necessary to write a program which could process the data taken, discriminate between random noise and real signals with a trigger parameter, and calculate the area of the pulses. From the National Instruments come out files in which are saved the waveform of those signals with higher amplitude than the threshold set by the Discriminator. Each waveform is a set of 1000 points, corresponding to 800 ns. A simple bash program count the number of waveforms.

The analysis program is written in C++ and uses the toolkit ROOT to analyze, plot and fit the data, and takes as input the two files (one for each channel, that is associated to a PMT). The code has two main cycles for the data analysis: during the first cycle, for both the channels it calculate the baseline, while during the second cycle, the area of the pulse is evaluated.

It has been chosen to take as baseline the fit made with ROOT of the first and the last 40 points of the waveform (32 ns): in this way, one can be sure of taking the pretrigger noise with the first 40 points, and to take into account the possible change of offset, using the last 40 points. In the second cycle it is used the baseline as the real zero of the signal, both for the activation of the trigger and the calculus of the area.

The level of trigger is set as parameter at the beginning of the program, and it does not change. To calculate the area of the events that successfully pass the trigger, the algorithm takes 20 points before the one that activate the trigger, and 20 points after the signal falls back below trigger. A flag is set in order to prevent the retriggering after the second trigger worked. In this way, the areas calculated from both PMTs are saved on the same file, in which also are saved the time of trigger, for the beginning of the signal and the end of it, and a coincidence flag.

From the data it can be seen some events with “positive” area. These are due to a saturation of the electronic signal (see Figure 3.19), caused by a non-optimal choice of the dynamic range for the data acquisition.

Main aim of this measure is to understand the features of the coincidence events. In

---

*A large dynamic range provides a large working window, but less precision on data, while a smaller dynamic range can cause the saturation of the signal if this has a large energy.*
3.5. PMT coupling

order to study this, it has been performed a plot of the product of the two areas versus the time of the trigger. In particular, it has been taken the time of the first PMT’s trigger minus the time of the second PMT’s trigger, so in the negative part of the y-axis there are those events which have been triggered first from the first PMT and then from the second one. On the positive part, instead, there are events seen first from the second PMT and later from the first one. There are two noticeable things: looking at Figure 3.21, one sees that around ±50 ns there are more events, while looking at Figure 3.23, it can be seen that there are some events around the zero, isolated from the others. The events around 50 ns are afterglows (an example in Figure 3.20). It can be easily seen that, increasing the voltage – i.e. the gain – the area of the signals also increases. Another feature is important to underline: there are more events in the negative part of the plot, around -50 ns, than in the positive part. This means that these events come from the trigger of PMT-1. In Table 3.9, it is shown the ratio of afterglow events with respect to the total number of events, for each PMT.

<table>
<thead>
<tr>
<th>Gain</th>
<th>PMT-1</th>
<th>PMT-3</th>
<th>PMT-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$3 \times 10^6$</td>
<td>37%</td>
<td>4%</td>
<td>4%</td>
</tr>
<tr>
<td>$5 \times 10^6$</td>
<td>44%</td>
<td>4%</td>
<td>4%</td>
</tr>
<tr>
<td>$7 \times 10^6$</td>
<td>48%</td>
<td>7%</td>
<td>7%</td>
</tr>
<tr>
<td>$10 \times 10^6$</td>
<td>54%</td>
<td>7%</td>
<td>8%</td>
</tr>
</tbody>
</table>

Table 3.9: Ratio of afterglow events with respect to total events

From this Table it is possible to infer that not only PMT-1 has a higher dark rate
3.5. PMT coupling

Figure 3.20: An event followed by an afterpulse, enhanced by the blue line around -75 ns than the other two, but moreover it makes more afterglows. As expected, the number of afterglow events increases with the growth of the gain.

It has been defined, as coincidence, an event happening in both PMTs in 40 ns of time, so these events around zero are real coincidences. About this, a last consideration can be done about the coincidence events with large area, clearly visible in Figure 3.23. These events are probably due to Cherenkov events inside the two window glasses of the facing PMTs: their rate has been found compatible with a rough estimation of cosmic rays flux in the windows area.
3.5. PMT coupling

Figure 3.21: Afterglow region around $\pm 50$ ns
3.5. PMT coupling

Figure 3.22: Afterglow region around ±50 ns

(a) Gain $7 \times 10^6$

(b) Gain $10 \times 10^6$
Figure 3.23: Example of large area events due to Cherenkov emissions in the glass window of the PMTs
3.6 Conclusions of the characterization tests

After the tests for the characterization of three PMTs Hamamatsu R11065-20 MOD and one R11065-20 standard, it is possible to define a response for each PMT from the point of view of the dark rate, of the gain and of afterglows.

During the first phase of the test, one of the two PMTs originally sent from Hamamatsu (PMT-2) has been found not working correctly: it was possible to understand very quickly that the problem was due to a leak in the vacuum tube, with the presence of many ions causing afterpulses. This PMT has been sent back to Hamamatsu; later they sent to LNGS a PMT R11065-20 standard, which has been used for the comparison with the MODs. The results of the other PMT tests show an uneven behaviour: the two PMT MODs (PMT-1 and PMT-4) seems very different to each other, while PMT-4 is very similar to PMT-3 (the standard one). Here, a brief summary of the characteristics found.

The test on the voltage dividers shows a higher P/V when using the negative HV supply; moreover, the distortion of the output signal during the use of the positive one, set the choice of using the voltage divider for negative HV supply for the next measurements. The average dark rate at gain $7 \times 10^6$ has been found to be $1258.1 \pm 1.1$ Hz for PMT-1, $211.1 \pm 1.0$ Hz for PMT-3 and $268.5 \pm 0.4$ Hz for PMT-4. The temperature plays a fundamental role in the dark rate, changing of about 4.5 % every 1 °C.

For what concern the gain, the three PMTs need different voltage supplied in order to have the same gain. The PMT-1, in particular, needs an extremely high voltage supplied as working conditions, higher than the recommended from Hamamatsu to reach the nominal gain. The study of the afterglows confirms that PMT-1 has a higher dark rate than PMT-3 and PMT-4 and higher probability to make afterglows. Increasing the gain of a factor of 1.5 provokes a growth in the afterglow rate in the order of 10% for PMT-1, while for the other two the growth is only in the order of few percent.
3.6. Conclusions of the characterization tests
Chapter 4

Tests of PMTs-crystal system

After the characterization of all of the three PMTs, the two MOD have been used in the coupling to a sodium-iodide doped with thallium (NaI(Tl)) crystal. The main goal of the tests of PMTs coupled to the crystal is to have an experimental set-up enough similar to the one that there will be in SABRE PoP, in order to understand how to perform the relevant measurements and to optimize the electronics. Specifically, these tests permit to calculate the Light Yield (LY), that is a property related to the quantity of light produced by the crystal during an event, to the quantum efficiency of the PMT and to the optical coupling made between them. Then, some measurements of calibration can also be performed, using radioactive source such as americium and uranium, which have γ peaks at known energy. The tests have been done at a first stage in the external laboratories, with a small lead and copper shielding against the natural radioactivity, and then underground, to be completely shielded from the cosmic rays (in particular, from muons).

4.1 Experimental Setup

The crystal used in these measurements is a 1.7-kg $3' \times 4''$ cylindric standard purity NaI(Tl) produced by Hilger Crystals Ltd. The crystal was encased in copper, with quartz windows and a cover of reflecting material along its side. The set-up for the tests have been modified: a new external enclosure made by copper has been realized. In Figure 4.1 it is possible to see the new enclosure chosen to house the crystal with the PMTs.

An optical gel has been spread on the PMTs window surface to couple the PMTs with the crystal, and the same metallic flange as the one seen in Chapter 3 is put around the PMTs to block them. In order to keep the crystal and the PMTs on axis with each other a proper frame has been realized. The crystal lateral surface is optically masked by a PVC cage (see Figure 4.2).

The electronics used in these measurements is the same as already mentioned in the previous Chapter. Let us summarize it:

- 2 PMTs MOD facing the crystal;
- 2 voltage dividers for negative voltage supply;
4.1. Experimental Setup

Figure 4.1: The new enclosure and the PMTs coupled with the crystal

- 1 voltage supply NHQ 202M 2x2kV/6mA double channel;
- 1 oscilloscope Teledyne LeCroy HDO6104;
- 1 CAEN Quad scaler-preset counter timer, mod. 145;
- 1 CAEN 6 channels Discriminator, mod. 224;
- 1 timing unit CERN n. 2255;
- 1 double manual programmable Logic Unit.

In Figure 4.3, it can be seen a schematic representation of the set-up used.

The gain chosen to perform all these tests is \(7 \times 10^6\).

Because these tests have the aim to catch the real signals coming from the crystal, that is when both PMTs see the light, it is necessary since the beginning to define when two signals can be considered “in coincidence”. The time window in which the signals are defined as coincident should not be too large, because otherwise too many random coincidences can go in the measure, but on the other hand not too small, or there is the risk to lose some of the real coincidences. The Discriminator threshold needs to be carefully chosen, in order to be sensitive to single photoelectron signals at low energy but still rejecting the noise.

To choose these parameters, a study of the rate as a function of the Discriminator threshold and the time window width has been done. In Table 4.1, it is shown the result of the study performed choosing a threshold of 1/3 of pe, 1 pe, 2 pe and 3 pe, and a time window of 200, 300, 500 and 600 ns. It can be seen that the main difference stays in the threshold level, in particular choosing a threshold higher than 1/3 pe does not change dramatically the results. As expected, the increase of the time window width, induces a growth on the number of random coincidences.

After these measurements has been chosen a time window width of 200 ns, without a fixed threshold.
4.2 External Laboratories

A small shielding against the natural radioactivity can be done using plates or bricks of lead. An additional protection is to put between the enclosure and the external shielding of lead, a layer of 2-3 cm of copper, particularly near the crystal region. This is needed in order to shield the detector from the background induced by the lead shield itself, in particular by the $^{210}$Pb isotope. This is a long lived isotope (lifetime $\sim$22 years) which is present in traces in natural lead. At low energies $^{210}$Pb produces a gamma peak between 40 and 60 keV and a continuum beta background elsewhere ($Q$-value = 63.5 keV). In Figure 4.4 can be seen the enclosure partially covered by the shielding of lead.

4.2.1 Measurements

First measurements have been performed at low gain, $3 \times 10^6$, in order to understand if everything was working in the right way. It has been taken the internal background mea-
4.2. External Laboratories

**Figure 4.3:** Schematical representation of the set-up used for the PMTs coupled with the NaI(Tl) crystal

### Table 4.1: Study of coincidence rate at different thresholds and time window widths. Here the average with the correspondent standard deviation

<table>
<thead>
<tr>
<th>Gain: $7 \times 10^6$</th>
<th>Time Window [ns]</th>
<th>Rate of coincidences [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Threshold: $1/3$ pe</td>
<td>200</td>
<td>1470 ± 277</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>1553 ± 436</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>3085 ± 947</td>
</tr>
<tr>
<td></td>
<td>600</td>
<td>3363 ± 511</td>
</tr>
<tr>
<td>Threshold: 1 pe</td>
<td>200</td>
<td>21 ± 1</td>
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<tr>
<td></td>
<td>300</td>
<td>26 ± 1</td>
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<td></td>
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<td>Threshold: 3 pe</td>
<td>200</td>
<td>18 ± 1</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>18 ± 1</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>19 ± 1</td>
</tr>
<tr>
<td></td>
<td>600</td>
<td>19 ± 1</td>
</tr>
</tbody>
</table>
4.2. External Laboratories

Figure 4.4: The partial shielding made by bricks and plates of lead. In the inner part, before the enclosure, a thin layer of copper has been made around the crystal region.

...sure and, then, a measure with two different sources: a source of $^{241}\text{Am}$ with activity of $\sim 1 \text{kBq}$, and a source of natural uranium rich of $^{238}\text{U}$ and $^{235}\text{U}$ with natural abundancies$^1$, drowned in epoxy resin and with activity of $\sim 4 \text{kBq}$. The americium has been chosen because it has two lines well recognizable at low energy, in particular one at 59.5 keV and the other (that is a overlap of two lines) at 26.3 keV. The uranium, on the other hand, has many easily identifiable $\gamma$ lines (from its decay chain) but at higher energy, from the four nearby lines at 186, 242, 295 and 352 keV, until even higher at 609 keV, at 1120 keV and 1765 keV. The sources have been put between the enclosure and the copper layer, very close to the crystal. These measures showed the awaited lines both for americium and for uranium decay chain.

The differences in the expected spectra from these two sources lead one to choose accordingly the dynamic range of the measurements; with the americium source, the relevant part of the spectrum is the low-energy one, so the measurements will be taken with a small dynamic range in order to have the best possible resolution of small signals. Otherwise, for the uranium source the large energy range of the gamma emitted, force to use a larger dynamic range to avoid saturation of the largest signals.

4.2.2 Data Analysis

The calibration in energy as it will be presented here is a simplified one. First of all because the accurate calibration of a crystal and PMTs system is not the aim of this work, and also because this crystal it is not the one that will be in the SABRE full-scale experiment, so it is not so important to have a precise calibration of it. Instead, it is interesting to understand how a calibration in energy works and to calculate a first estimation of the Light Yield.

One of the things to keep in mind while making an energy calibration is that the relation between incident gamma energy and light produced is not linear for most of the crystals.

---

$^1$That is, 99.28% of $^{238}\text{U}$ and 0.72% of $^{235}\text{U}$
The sodium-iodide is one of these cases: the conversion factor from charge to energy has to be evaluated at different energies, in order to be more truthful.

Let us see how to calibrate in energy and to extract the $\text{LY}$. In Figure 4.5 it is shown the americium spectrum at low energy. The two peaks have been recognized as the 26.3 keV and the 59.5 keV lines: it is needed to make a fit of the 59.5 keV line to have the position of the peak and its width, in unit of area (nVs). The peak position is used to extract the number of photoelectrons produced by the 59.5 keV $\gamma$, while the width ($\sigma$) is related to the energy resolution of the crystal. It has been chosen to fit only the 59.5 keV peak because the other one seems too large to be a single line.

![Figure 4.5: Fit of the 59.5 keV americium line in the low energy spectrum](image)

From the fit, the 59.5 keV line is located at -6.29 nVs and has a $\sigma$ of 0.45 nVs. Knowing that at gain equal to $3 \times 10^6$, from 1 single photoelectron the PMT collects a charge of -12 pV s, the Am peak corresponds to $\sim$524 photoelectrons, which means a $\text{LY}$ around 8.8 phe/keV, while the $\sigma$ corresponds to 4.26 keV. The resolution is defined as the ratio between the Full Width Half Maximum (FWHM, also indicated as $\Gamma$) of the peak and the energy at which the line is located, that is, in this case, for 59.5 keV line $\Gamma \sim$ 10 keV, and the resolution at this energy is about 17%.

To this end, an uranium source has been used. Looking at Figure 4.6, there are some lines that are very well distinguishable from the continuum part of the spectrum. Fitting the peaks, one can make a Table as the 4.2 in order to calibrate from area to energy.

It is necessary now to define a general function, such as a polynomial function:

$$f(x) = a + bx + cx^2 + dx^3 + \cdots$$  \hspace{1cm} (4.1)

The calibration curve and its parameters can be seen in Figure 4.7.
4.2. External Laboratories

Figure 4.6: Uranium source spectrum

<table>
<thead>
<tr>
<th>Source</th>
<th>Area [nVs]</th>
<th>σ [nVs]</th>
<th>Energy [keV]</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Americium</td>
<td>-6.29</td>
<td>0.63</td>
<td>59.5</td>
<td>~24%</td>
</tr>
<tr>
<td></td>
<td>-30.04</td>
<td>2.05</td>
<td>352</td>
<td>~20%</td>
</tr>
<tr>
<td></td>
<td>-50.83</td>
<td>2.53</td>
<td>609</td>
<td>~12%</td>
</tr>
<tr>
<td></td>
<td>-85.83</td>
<td>3.66</td>
<td>1120</td>
<td>~10%</td>
</tr>
<tr>
<td></td>
<td>-115.49</td>
<td>3.02</td>
<td>1765</td>
<td>~6%</td>
</tr>
<tr>
<td>Uranium</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.2: Collected charge and its relative energy value, from americium and uranium spectra
4.3 Underground Laboratories

The basic set-up that has been realized in the external laboratories permitted to make a first study of the crystal properties, such as the light yield and the resolution. Cosmic muons, however, are very penetrating and still pass through this shield, impeding to study the background spectrum of the crystal. In order to have a better shielding, made by the mountains rock, it has been decided to go in the underground laboratories, at the southern part of Hall B. In Figure 4.8 there is a picture of the new shielding made by copper and bricks of lead.

4.3.1 Measurements

All the measurements taken underground have been done at gain $7 \times 10^6$. The method is the same as the one used in the external laboratories, that is performing a long time measure of the internal background, then adding radioactive source to measure its spectrum and calibrate in energy. The source used in these measurements was the already used natural uranium. The measurements have been performed using the oscilloscope with an external trigger fired by coincidences of both PMTs, with a threshold of -15 mV (corresponding to about 3 pe for each PMT).

4.3.2 Data Analysis

As already done in the external laboratories, let us now calibrate in energy using the same sources of americium and uranium.

Looking at the uranium spectrum, it is easy to recognize the same lines used before (see Figure 4.7: The energy calibration curve)
4.3. Underground Laboratories

Figure 4.8: The shielding made by an inner layer of 2 cm of copper, and bricks of lead outside, in an intermediate phase of assembly.

Table 4.3). The spectrum has been normalized dividing by bin width, in keV, and by the crystal weight. The calibration lead to evaluate the LY as $7.4 \text{ pe/keV}$ at gain $7 \times 10^6$.

<table>
<thead>
<tr>
<th>Source</th>
<th>Area [nVs]</th>
<th>$\sigma$ [nVs]</th>
<th>Energy [keV]</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Americium</td>
<td>-12.30</td>
<td>1.63</td>
<td>59.5</td>
<td>$\sim$31%</td>
</tr>
<tr>
<td></td>
<td>-73.0</td>
<td>2.04</td>
<td>242</td>
<td>$\sim$29%</td>
</tr>
<tr>
<td></td>
<td>-104.1</td>
<td>8.31</td>
<td>352</td>
<td>$\sim$19%</td>
</tr>
<tr>
<td>Uranium</td>
<td>-176.2</td>
<td>10.88</td>
<td>609</td>
<td>$\sim$15%</td>
</tr>
<tr>
<td></td>
<td>-312.6</td>
<td>17.56</td>
<td>1120</td>
<td>$\sim$13%</td>
</tr>
<tr>
<td></td>
<td>-480.0</td>
<td>18.09</td>
<td>1765</td>
<td>$\sim$9%</td>
</tr>
</tbody>
</table>

Table 4.3: Collected charge and its relative energy value, from americium and uranium spectra.

The uranium spectrum after the calibration in energy is shown in Figure 4.9a. After this, a measurement of the background has been taken (see Figure 4.9b). Then the background spectrum has been normalized using the differential rate unit (1 d.r.u. = 1 count/keV/day/kg), a unit of measurement usually used in rare event physics experiments. Another interesting feature to notice in the same Figure, in the region between 2 and 3 MeV, is a multi-peak structure due to $\alpha$ particles, generated by the decays of uranium and thorium inside the crystal.

Let us focus on this region (see Figure 4.10): there are at least three peaks constituted by $\alpha$ particles, whose energy appears lowered respect to $\gamma$s, due to the phenomenon called “quenching”. The quenching is the reduction of the light output of an event due to high ionization density or nuclear interaction of the incident particle. Ionization density quenching
4.3. Underground Laboratories

(a) The uranium spectrum after the calibration in energy

(b) The background spectrum after the calibration in energy, collected in 16 hours

Figure 4.9: The calibration in energy
occurs because scintillation light output depends on the number of excited luminescence centers, which itself depends on the positions of charge carriers relative to the luminescence centers and traps, the mean migration length of the carriers, and their energies [43]. Due to the quenching effect, $\alpha$s and high energy $\gamma$s are partially overlapped in the spectrum, even if of different energy.

![Figure 4.10: Zoom of the energy range in which the $\alpha$s appear](image)

To solve this problem and obtain a detailed spectrum of the $\alpha$ peaks, a dedicated run with high trigger level followed by Pulse Shape Discrimination (PSD) has been performed. It has been collected and saved 4751 waveforms, asking a trigger condition of -400 mV for at least 100 ns, applied to the PMT with lower dark rate (that is, PMT-4). For events of such large area, it is useless to ask for coincidences between the two PMTs, because this condition is always fulfilled. The waveform length is 5 $\mu$s, approximately divided in two equal parts before and after the trigger, for reasons that will become clear in the following section. The saved waveform represents the sum of the two channels of the PMTs. The recognition of the $\alpha$s has two main aims: an estimation of the quenching factor, and a first, simple measure of the internal radioactivity of the crystal, in particular the presence of uranium and thorium.

**Pulse Shape Discrimination: decay time of $\gamma$s and $\alpha$s**

To separate samples of $\gamma$s (or electrons, muons, ...) from $\alpha$s, it is customary to define a parameter $\tau$, that is the first moment of the time distribution of the scintillation pulse:

$$
\tau = \frac{\sum h_i t_i}{\sum h_i}
$$

(4.2)
where \( h_i \) is the pulse height at the time \( t_i \), and the sum is over 600 ns after the starting of the pulse [26]. It is clearly distinguishable, from Figure 4.11 the separation between two populations: the \( \alpha \) particles, which have shorter \( \tau \) (around 220 ns), and the \( \gamma \) particles (with \( \tau \sim 240 \) ns); it is also evident the multi-peak structure in the \( \alpha \) distribution.

![Figure 4.11](image)

**Figure 4.11:** The scatter plot of \( \tau \) (in ns) vs. area (in nVs), calculated within a 600 ns averaging time

### Quenching and internal radioactivity estimation

To better analyze the multi-peak structure, let us plot a histogram of only those events that lay below the line, showed in Figure 4.12.

To assign the \( \alpha \) energy to each peak, it is necessary to know which \( \alpha \) one expects to see in the uranium and thorium decay chains: in Table 4.4 and 4.5 are reported these values.

One of the decay in the thorium Table has a particularly interesting feature that helps in the identification of the event and the associated area: it is the so-called "Bi-Po" event of the thorium chain. This decay is effectively composed by two decays, one following the other within a very short time: there is a \( \beta \) decay of \( {}^{212}\text{Bi} \) followed by an \( \alpha \) decay of \( {}^{212}\text{Po} \), whose half-life is 299 ns. This means that, with a high efficiency, the \( \beta \) decay event can be found in the 2 \( \mu s \) time window preceding the \( \alpha \) event. Due to the waveform composite form, often these events escape the selection based on \( \tau \) parameter. In Figure 4.13 can be seen an example of one of these events.

Looking at the area of the \( \alpha \) decays of these events, one can obtain the mean value of 1120 nVs and this allows a first estimation of the quenching factor: \( Q(8780 \text{ keV})=0.59 \). Assuming a slowly increasing behaviour of \( Q \) as a function of the \( \alpha \) energy, one can tenta-
4.3. Underground Laboratories

Figure 4.12: $\alpha$ events after the PSD

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Energy [keV]</th>
<th>Intensity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{238}\text{U}$</td>
<td>4180</td>
<td>99.9</td>
</tr>
<tr>
<td>$^{234}\text{U}$</td>
<td>4750</td>
<td>99.8</td>
</tr>
<tr>
<td>$^{230}\text{Th}$</td>
<td>4660</td>
<td>99.7</td>
</tr>
<tr>
<td>$^{226}\text{Ra}$</td>
<td>4780</td>
<td>94.4</td>
</tr>
<tr>
<td>$^{222}\text{Rn}$</td>
<td>5490</td>
<td>99.9</td>
</tr>
<tr>
<td>$^{218}\text{Po}$</td>
<td>6000</td>
<td>99.9</td>
</tr>
<tr>
<td>$^{214}\text{Po}$</td>
<td>7690</td>
<td>99.9</td>
</tr>
<tr>
<td>$^{210}\text{Po}$</td>
<td>5300</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 4.4: $\alpha$s from $^{238}\text{U}$ decay chain

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Energy [keV]</th>
<th>Intensity×BR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{232}\text{Th}$</td>
<td>3990</td>
<td>99.9</td>
</tr>
<tr>
<td>$^{228}\text{Th}$</td>
<td>5370</td>
<td>99.4</td>
</tr>
<tr>
<td>$^{224}\text{Ra}$</td>
<td>5690</td>
<td>94.9</td>
</tr>
<tr>
<td>$^{220}\text{Rn}$</td>
<td>6290</td>
<td>99.9</td>
</tr>
<tr>
<td>$^{216}\text{Po}$</td>
<td>6780</td>
<td>99.9</td>
</tr>
<tr>
<td>$^{212}\text{Bi}$</td>
<td>6060</td>
<td>35.9</td>
</tr>
<tr>
<td>$^{212}\text{Po}$</td>
<td>8780</td>
<td>64.1</td>
</tr>
</tbody>
</table>

Table 4.5: $\alpha$s from $^{232}\text{Th}$ decay chain
4.3. Underground Laboratories

Figure 4.13: A Bi-Po event: the $\beta$ decay of $^{212}$Bi, followed by the $\alpha$ decay of the $^{212}$Po after $\sim 500$ ns

tively assign the energy of the decays to each peak seen in Figure 4.12. Starting from the lowest, well isolated peak around 650 nVs, one can assign this peak to the three nearby $\alpha$s of the uranium chain at 4660, 4750 and 4780 keV, clearly not resolved. A gaussian fit of this peak has been done and the mean value found to be 646 nVs, corresponding to a mean energy of 4730 keV, giving a quenching factor of 0.562. Repeating this procedure to each structure in the Figure, one obtains the energy calibration for $\alpha$s (Figure 4.14) and the quenching factor as a function of energy, varying linearly from 0.56 to 0.59 in the range of 4500 keV to 9000 keV.

A multi-gaussian peak analysis has been performed considering contributions from 7 peaks (or group of peaks); the global fit result is visible in Figure 4.14 as a blue line, and its reduced $\chi^2$ is 1.04. From the amplitude of each structure, one can also extract the activity of uranium and thorium contained inside the crystal, and have information about the activity of each isotope in the chains, allowing a study regarding the eventual presence of secular equilibrium break. Doing this, one has to consider that, due to the limited energy resolution of the crystal, several lines from different nuclides can overlap: for example, it is impossible to disentangle the activities of $^{234}$U and $^{230}$Th (of the uranium chain).

Another comment about the Figure is that the peak at 6780 keV, due to $^{216}$Po decay, is suppressed as an effect of the dead time necessary to the oscilloscope to save a waveform, that is of the same order of magnitude as its lifetime (0.145 s).

At this time it is possible to give an estimation of the activity of the crystal in terms of different nuclides in the thorium and uranium chains, as can be seen in Table 4.6. A careful estimation of the errors lays outside the scope of this simplified calculation, but some comments are in order. Due to the statistics of each peak, in the range of 200-500
4.3. Underground Laboratories

Figure 4.14: Fit of the $\alpha$ peaks with 7 gaussians. The histogram bin width is 4 nVs events, one can make a conservative estimation of the statistical error, varying among the 5% and 7%. Considering also some systematics coming from the fitting procedure, the error can be set at $O(10\%)$.

<table>
<thead>
<tr>
<th>Nuclides</th>
<th>Contamination [mBq/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{238}$U</td>
<td>$\sim$0</td>
</tr>
<tr>
<td>$^{234}$U</td>
<td>0.7</td>
</tr>
<tr>
<td>$^{230}$Th</td>
<td>0.7</td>
</tr>
<tr>
<td>$^{226}$Ra, $^{222}$Rn, $^{218}$Po, $^{214}$Po</td>
<td>2.0</td>
</tr>
<tr>
<td>$^{210}$Pb, $^{210}$Po</td>
<td>3.7</td>
</tr>
<tr>
<td>$^{232}$Th</td>
<td>$\sim$0</td>
</tr>
<tr>
<td>$^{228}$Ra, $^{228}$Th, $^{224}$Ra, $^{220}$Rn, $^{216}$Po</td>
<td>2.1</td>
</tr>
</tbody>
</table>

Table 4.6: Contaminations of the NaI crystal

Looking at the values in the Table, one can also observe that in both the decay chains there are evidences of breaking of the secular equilibrium. In particular, the upper part of the chain seems to be depleted with respect to the lower one, i.e. below the radium. Moreover, as observed also in other cases, in this crystal additional contaminations from $^{210}$Pb are present.

As last observation, looking again at Figure 4.9b, one can see that at this level of measurements there are no traces of $^{40}$K $\gamma$-ray at 1461 keV, so no meaningful limit on this
4.4 Conclusions of the PMTs-crystal system tests

The PMT-crystal system tests have led to estimate several properties deduced both from using radioactive sources, such as the americium and the uranium, and from intrinsic background measurements.

A first estimation of the Light Yield has been performed: for these measurements the americium source spectrum has been used first at gain $3 \times 10^6$, resulting a LY of 8.8 phe/keV, and then at $7 \times 10^6$, with 7.4 phe/keV. This second value is more accurate than the first one because of the higher gain which permits a better separation of the peaks and it is less sensitive to baseline variations.

A calibration in energy of $\gamma$s has been done, in the external and in the underground laboratories, using in both cases the uranium source. In particular, the calibration of the internal background spectrum taken underground allows a study of the $\alpha$ particles produced by uranium and thorium decay chains.

Thanks to a Pulse Shape Discrimination that permits to discriminate between high energy $\gamma$s and $\alpha$s, an estimation of the quenching factor of the crystal has been done, with the reconstruction of the $\alpha$ energy of this part of the spectrum. Moreover, the identification of the main $\alpha$s leads to extract the activity of uranium, thorium, and the daughter element inside the crystal.

The test system realized, and the understanding and optimization of the procedure for the data acquisition, is a preparatory activity which could increase the experience of the SABRE group, for the moment when the ultra-pure crystals will arrive at the SABRE PoP facility.
Conclusions

During these last few years, the dark matter has been at the center of a large investigation, from particle physics to astrophysics and cosmology, both from a theoretical and from an experimental point of view. An enormous effort has been made in order achieve the discovery of DM and both direct and indirect search techniques were employed, plus a research of production at colliders. Direct search also include the seek of the annual modulation: a DM signal in an Earth-based detector is expected to modulate yearly, due to the change of the Earth’s speed relative to the galactic halo reference frame.

The interaction of the dark matter with baryonic matter are characterized by a tiny cross section – still not well-known. A direct search detector should therefore be distinguished by its exceedingly low intrinsic radioactivity, and shield from cosmic rays and other environmental radioactivity. Typically, on doing so, an experiment is better placed inside an underground laboratory.

An experiment called DAMA/LIBRA, located in the Gran Sasso National Laboratories (LNGS) in Italy, keeps a longstanding and high-significance (9.3 \( \sigma \)) result, consistent with the scenario of an elastic and spin-independent nuclear scattering of DM particles which is modulated yearly with the right phase and period as awaited. The DAMA signal is in tension with null results from other direct search experiments, such as XENON, LUX, CDMS and CRESST. Nevertheless this comparison is not conclusive, since different assumptions and detectors are used. A confirmation by an independent NaI experiment is still missing.

The Sodium-iodide with Active-Background REjection (SABRE) is a thallium-doped sodium-iodide experiment designed to look for dark matter through the annual modulation signature. The SABRE detectors consist in an array of NaI(Tl) crystals, 5-kg each, for a total mass of \( \sim 50 \) kg. The signals from crystals are read by low radioactivity, high quantum efficiency, low dark noise PMTs, directly coupled to the crystals (two PMTs for each crystal) and encased in a OFHC copper enclosure. A liquid scintillator, contained by a steel vessel, operates as active veto against external and most importantly internal backgrounds. Layers of additional passive shielding are made using highly pure water and lead.

The experiment follows a two-phase approach: during the first phase, SABRE will be operated at LNGS as a Proof-of-Principle with the goal of demonstrating the lowering the background in the region of interest for dark matter detection at a level that is significantly below the one observed by DAMA/LIBRA. The second phase will consist of two full-scale NaI(Tl) detector arrays located one at LNGS, and the other in the Stawell Underground Physics Laboratory (SUPL) in Australia. This operation will strengthen the reliability of
the result against possible seasonal systematic effects. For what concern the PMTs, the choice of not using a light guide but to directly couple the PMTs to the crystal improve the light-collection efficiency but sets a radiopurity goal for the PMTs. A high performance is also sought: characteristics such as the quantum efficiency, the gain and the dark noise have to be studied and optimized. The choice of Hamamatsu R11065-20 PMTs has been made because of their high quantum efficiency, but the high dark rate in a room temperature environment is still a problem. During the construction of the SABRE experiment, a R&D on the improvement of these PMTs has been pursued. A new model of Hamamatsu PMT, called R11065-20 MOD has been built with the use of a superbialkali photocathode, which should allow a high quantum efficiency keeping the dark noise low even in a non-cryogenic environment.

In this work, a characterization of three prototype PMTs has been performed with a comparison with respect to a standard one. The characterization work can be divided in two parts, and proceeded as follows. A first effort consisted in the design and implementation of an experimental set-up for the test of the PMTs, including the machinery of custom mechanical parts, electronics of the voltage dividers and the data acquisition. After this arrangement, the features of each PMT such as the single electron response, the gain, the dark rate and the afterglow rate have been studied. During the first stages of the study, one of the three PMTs sent by Hamamatsu has been found with a leakage in the vacuum tube, that causes the presence of ionized gases responsible for afterpulses. This PMT has been replaced with a standard one by Hamamatsu, and this allowed to compare the two types of PMTs. The comparison showed uneven performances between the two MODs, while the standard PMT exhibited extremely good properties. According to Hamamatsu, the newness of this product is probably the main cause of this large variation among the same model of PMT. The PMT MODs have been called PMT-1 and PMT-4, while the PMT standard has been called PMT-3 (following the arriving order). The average dark rate at gain $7 \times 10^6$ has been found to be $1258.2 \pm 1.1$ Hz for PMT-1, $211.1 \pm 1.0$ Hz for PMT-3 and $268.5 \pm 0.4$ Hz for PMT-4. The temperature plays a fundamental role in the dark rate, changing of about 4.5 % every 1° C. The gain is another parameter of the PMTs according to which the PMT-1 differs deeply on the others. All of them have the expected linear trend for the characteristics $\log G - \log V$, but in order to reach the same gain for all the PMTs different voltage supply is needed. The study of the afterglows confirmed that PMT-1 has a higher probability to make afterglows than PMT-3. Increasing the gain provokes a growth in the afterglow rate order of 10% for PMT-1, while for the other two PMTs this growth is only in the order of few percent.

The next step has been a measurement of the light yield, achievable with a crystal-PMTs assembly. In order to perform this, the two MODs have been coupled to a test NaI crystal. To test the feasibility of background measurements with a preliminary pulse shape discrimination, the set-up has been installed in the underground facility of SABRE and – thanks to the help of highly qualified staff of the laboratories – several spectra have been acquired using radioactive sources to make a calibration in energy. Then, the data of the intrinsic
background of the crystal have been analysed, allowing a first comprehension of the contamination in the crystal by studying the spectra and separating $\alpha$ from $\gamma$ events using a parameter related to the decay time of pulses as a function of collected charge (or energy).

In conclusion, the low dark rate, the small afterglow effects and the high gain at nominal voltage show a good possibility for the PMT MOD to be chosen as the working solution for the SABRE experiment, provided the company can match the performances of the best of the units (PMT-4) during their future production. The light yield value shows a better efficiency than the DAMA experiment one, but it could be further improved. Finally, the background identification method has been proven reliable with the standard purity crystal, providing a good procedure which can be used in the next future. The experimental set-up developed for these measurements will be also used for the definition and optimization of the signal to noise discrimination strategies. This will be an essential step towards the lowering of the threshold. All the experience acquired will be useful during the handling and testing of the high purity crystal that will be used in the SABRE PoP.
Bibliography


[34] [http://darkmatter.org.au/node/9](http://darkmatter.org.au/node/9)


Acknowledgements

Il momento in cui si scrivono i ringraziamenti è per me la parte più bella del periodo di tesi: è qui, infatti, che posso tirare le somme e ripensare a tutti quelli che, in un modo o nell’altro, ne hanno fatto parte e mi hanno supportato e soprattutto.

Da chi cominciare dunque se non da chi mi ha permesso di arrivare fino a qui: il più grande, il primo grazie va ai miei genitori, che non hanno mai smesso di credere in me, di sostenermi nelle difficoltà, di starmi accanto anche quando sbagliavo (e io sbaglio spesso). Sono come sono grazie a loro, a come mi hanno educata ma soprattutto al grande amore che mi hanno dato sempre sentire. Sono un esempio di vita per me. Vi devo tutto. A mia sorella, che è purtroppo lontana da me, da noi, ma solo fisicamente, perché nel mio cuore è sempre presente: grazie per tutte le risate, le litigie (soprattutto quelle), i giochi, le confidenze. È una forza e sembra non rendersene conto! Ho anche una famiglia allargata fantastica, e anche a loro devo dire grazie perché mi hanno cresciuta. Grazie ai miei zii Giannina e Mario per esserci sempre, a mia cugina Anna che per me è come una sorella maggiore, a Said e a Rebecca (anche se mi fa i dispetti e mi chiama “Marta”), allo zio Massimo, e grazie anche a tutto il resto della tribù che se li citassi tutti, dovrei fare una tesi a parte. Grazie ai miei nonni Luli e Angelo, e alla mia nonna Pina: sono le radici della mia storia.

Dopo la mia famiglia, come non ringraziare le mie amiche di una vita: Sery, Sabry, Ery, Kry, Miry, Arj. Quante pazzie, quante risate, quante lacrime! Nonostante le strade diverse che abbiamo imboccato, nonostante le vie separate e la distanza che c’è tra noi, quando torno a casa voi ci siete sempre, e casa lo è proprio anche grazie a voi. Alla mia amica Otta, a cui non riesco a stare vicina come vorrei ma che non vorrei mai perdere. Grazie a Daniel, compagno di discussioni più o meno serie, da cui imparo sempre qualcosa di nuovo. Nel mio percorso di studi, ho incontrato tantissime persone che si sono riveleranno non solo nella mia crescita professionale, ma anche e soprattutto personale. La prima persona che ho conosciuto e che mi ha accompagnata in tutti questi anni è la mia amica (moglie) Michela, che fin da subito con me non si è fermata all’apparenza di ragazza casinista, ma ha trovato il mio meglio e lo ha coltivato con la sua costante presenza e la sua saggezza. Grazie perché mi ha sempre capita subito come se fosse un’estensione di me stessa. Vorrei ringraziare anche la Vale, che pure mi è stata accanto in questi anni, e tutti i compagni particellini: la Dia, Vector, Silvia e Baso, che mi ha sopportato fino all’ultimo in ufficio.

Non sempre le amicizie nascono fin dal primo momento: amicizia più tardiva è stata quella nata tra me e Carlo, tardiva ma così grande, che nemmeno i suoi tricipiti possono eguagliarla. Scherzi a parte, è la persona più leale e sincera che io conosca. Con Carlo è
arrivato Pier, una persona così speciale che mi mancano le parole appropriate. È speciale e non si può descrivere come. È semplicemente il pazzo, pazzo Pier. Anche quella con Nico è stata un’amicizia sbocciata tardi, e “sbocciata” in effetti è la parola giusta: quante bevute e mangiate fatte insieme, nella casa a Piola, con i suoi incredibili coinquilini! Pure Nico è una di quelle persone buone, leali e così incredibilmente piene di vita, che fai fatica a starci dietro. Ci sono anche persone che credevi di non poter sopportare, e che invece ti sorprendono e ti catturano con la loro personalità ambigua e affascinante: con Roby è stato così, un invito casuale seguito da un’amicizia di quelle liberatorie, in cui ti confidi e non ci pensi più. L’invito casuale è stato anche l’inizio di quella grande avventura che è l’amicizia con la Silvia (la mia Silvia). Lei è una di quelle persone così buone, che deve per forza far finta di essere perfida, anche se non ci crede nessuno. Quante cose mi ha fatto scoprire e riscoprire di me stessa, quante cose mi ha insegnato, e quanto abbiamo condiviso: sembra una vita che ci conosciamo, e non soltanto due anni. Grazie a lei ho potuto conoscere altre persone che hanno iniziato a far parte delle mie giornate e le hanno rese più divertenti e semplici da vivere: Salvo, Simo, Penny, Jacopo, Carlo, Ruzza, Enrico e Andrea. Durante tutti questi anni, gli scherzi tra me, Giorzino e Da Col hanno reso pure le mie giornate migliori, soprattutto la festa della donna. E non posso citare tutti gli altri millemila amici fisici (e non) che ora hanno spiccato il volo e sono da qualche parte nel mondo, o stanno ancora studiando o si laureano con me, ma anche a loro va il mio grazie, perché ci sono stati e ci hanno fatto perdere e gioire con me. La mia casa a Milano è stata il centro di sviluppo di queste amicizie: un grazie anche a Giada e Giuliano, perché con loro questa casa è davvero “casa”. Scegliere la tesi non è mai facile, ma te lo senti quando trovi “quella giusta”. È stata giusta grazie al mio relatore Davide D’Angelo, a cui non dirò mai grazie abbastanza per avermi dato la possibilità di lavorare in uno dei posti più entusiasmanti in cui io sia stata finora: i Laboratori Nazionali del Gran Sasso. Qui ho potuto non solo partecipare a un progetto che ho sentito davvero mio, ma soprattutto perché ho conosciuto delle persone meravigliose che mi fanno fremere dalla voglia di tornare là. La mia relatrice esterna, Mackalena Antonello, che nonostante i disagi e le difficoltà che comportano il ruolo di neomamma, ha trovato il tempo e la forza per seguirmi; Chiara Vignoli, la responsabile nazionale di SABRE, che si è presa cura di me come una mamma ma che ho conosciuto sulla pista da ballo come un’amica; tutto il resto della collaborazione (italiana e non), che mi ha aiutata tante volte e mi ha fatto sentire partecipe veramente, e non solo una piccola e ingenua laureanda. Tutti i ragazzi dei laboratori, che mi hanno fatto da famiglia e da amici quando famiglia e amici erano lontani: Laura, solare e coinvolgente, che mi ha aiutata a integrarmi fin dall’inizio; Fede, una delle prime che ho conosciuto e la più matta che ho incontrato; Valentyna, così dolce e così forte; Vale, che valentissima, ma col suo accento e la sua simpatia le si perdona tutto; il paziente Marco D’Incecco e il folle George; e tutti gli altri che mi fanno mancare terribilmente il Gran Sasso. Tornerò presto.

La persona più importante che ho conosciuto al Gran Sasso non l’ho ancora nominata perché merita un post in parte: Giuseppe, senza il quale banalmente non avrei potuto fare e scrivere questa tesi, ma mi viene da ridere a scrivere così perché Giuseppe ha fatto molto di più. Giuseppe è stato un amico, un padre, una madre, un fratello, una guida, un assistente. Ha risposto alle mie domande sulla Vita, l’Universo, Tutto. È stato un punto
di riferimento per me quando ne avevo bisogno e anche quando non ne avevo bisogno, mi è stato vicino in tutti i modi in cui qualcuno può occuparsi di un’amica (o di una sua non-laureanda), e mi fa capire ogni giorno che è esattamente questa la persona e il Fisico che spero di diventare.

Infine, devo riuscire a trovare le parole per ringraziare un’altra delle persone più belle che io abbia mai avuto la fortuna di incontrare: il mio ragazzo, Andrey. Quest’ultimo anno è stato speciale ed emozionante sotto molti punti di vista, e lui è una delle persone che hanno contribuito a renderlo tale. Da quando ci siamo incontrati, non è passato giorno senza che io potessi imparare qualcosa di nuovo, sul mondo, su di lui, su di me. Il suo entusiasmo e la sua voglia di sapere sono qualcosa che mi sprona tutti i giorni, la sua pazienza infinita, la sua dolcezza e il suo continuo supporto mi danno la forza di affrontare il mondo. Grazie.