Directional dark matter search with the NEWSdm experiment

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Introduction

Compelling evidences indicate that the ordinary barionic matter is only \( \sim 5\% \) of the total mass-energy content (\( \sim 15.6\% \) of the matter content) of the universe. The rest of the matter is somehow “dark”: it does not interact by means electromagnetic force and represents the \( \sim 26.5\% \) of the total content (\( \sim 84.4\% \) of the matter content) of the universe. It is known to exist because of its gravitational effects at both galactic and extra-galactic scales. The remaining dark energy is still completely unknown.

The most convincing dark matter (DM) candidate filling the galaxy is the Weakly Interacting Massive Particle (WIMP), with a mass in the range from 1 GeV to 10 TeV. WIMP candidates are cold, that is not relativistic, they interact only by means of weak and gravitational forces and are massive.

DM has not yet been directly detected and its nature remains unknown. Many efforts are being spent to directly detect it searching for WIMP-induced nuclear recoils. Among the DM direct detection experiment an increasing interest is held by directional experiments aiming at reconstructing both the energy and the track direction of a WIMP-induced nuclear recoil. Since WIMPs, as seen by the Earth, should mostly come from the direction of Cygnus constellation, the recoil rate would then peak in the opposite direction. Thus the directional signature would be a distinct and unambiguous dark matter signal, indicating its galactic origin.

This thesis work was carried out in the framework of the Nuclear Emulsion for Wimp Search with directional measurement (NEWSdm) experiment, being designed for the detection of WIMP-induced nuclear recoil tracks by means of a new generation nuclear emulsions, the Nano Imaging Tracker (NIT), whose grains have linear dimension of \( \sim 45 \) nm, allowing to detect sub-micrometric tracks.

As for all DM direct detection experiments neutron-induced nuclear recoils represent the most dangerous background. The purpose of this thesis is to find through Monte Carlo simulations, the best configuration for the shield that will surround the NEWSdm detector. The aim is to keep the external background below a reasonable level (defined as \( \sim 1 \) event/(10 kg\text{yr}). These results will be used as input for the preparation of the Technical Design Report (TDR) due by the NEWSdm collaboration in spring 2019.

Finally I describe the work carried out to upgrade of the illumination system for the super-resolution optical microscope, to be used for the read out of nuclear emulsions, since I was involved in its assembly.

This thesis presents the following chapters:
• Chapter 1: the historical course of the experimental hints that highlight the presence of dark matter is reviewed. Then a brief description of different dark matter candidates is carried out;

• Chapter 2: it is devoted to the description of the NEWSdm experiment, highlighting the features of NIT and the readout strategy of emulsion films by means of optical microscopes;

• Chapter 3: after a brief description of neutron interactions with matter, the characterization of the muon flux at LNGS, responsible for the neutron production in the rock as well as in the shield and detector materials is given. Finally the results of the shield simulations are reported;

• Chapter 4: the description of the European Scanning System and the R&D conducted by the Naples OPERA group for the development of a super-resolution optical system is carried out. Then the implementation of a new illuminating system for the super-resolution optical microscope is described.
Chapter 1

Dark matter: an overview

One of the greatest challenges coming from cosmology and astroparticle physics concerns the problem of what kind of matter fills our universe. This is not a simple question to answer. Already in the 30s of the 20th century the first indications that an “unusual” kind of matter could permeate the universe appeared. The scientific community refers to it as “dark matter” (DM). Many progresses since that time were made to better understand this puzzle. The final step is a direct experimental evidence, which is the aim of a large number of underground experiments involving many scientists.

In this chapter we will review the hints for the presence of dark matter in the universe, derive some quantitative estimates of the amount of this matter in the universe and finally we will describe some possible candidates.

We will follow the approach of reference [1].

1.1 Experimental hints

The first hypothesis of a new form of matter, the dark matter, is due to the astronomers Jan Hendrik Oort and Fritz Zwicky who, separately, studied the orbital velocity of stars and galaxies, respectively.

Later, many other evidences for dark matter were found, such as gravitational lensing, collision of galaxy clusters, the study of Cosmic Microwave Background (CMB). We are now describing the main compelling evidence for DM in the universe.

1.1.1 Orbital velocities

In a work of 1932 [2] J.H. Oort studying the orbital velocity of stellar systems perpendicular to the galactic plane found that their velocity exceeded the escape one. For this reason for the first time it was postulated the presence of some type of non luminous mass in the universe. It is necessary to underline that, besides this idea, Oort did not rule out more conventional hypotheses such as the presence of halfway dust and matter that overshadow

\footnote{The velocity of the stars was determined measuring the Doppler shift of the stars themselves.}
up to 85% of the light from galactic center or that the measurements of stars velocity were simply wrong.

In the same period the Swiss astronomer Fritz Zwicky in a work of 1933 [3] and one of 1937 [4] also found indications of the presence of non-luminous mass on intergalactic scale. Observing Doppler shifts of galactic spectra of Coma cluster he measured the velocity dispersion of the single galaxies. With an analysis based on the virial theorem \(^2\) he could estimate the cluster’s mass. He found a value ten times larger than the luminous mass. So the largest part of the Coma cluster appears to be non-luminous.

![Figure 1.1: Measured rotational velocities (red points) of HI regions in NGC 3198 compared to an idealized Keplerian behavior (dotted line) [8].](image)

The final proof of the presence of non-luminous matter through the study of rotation curves came in the 70’s and 80’s with two works of Vera Rubin and collaborators[5, 6]. Before showing the results of Rubin’s works we explain what is the expected trend of rotation curve for an object rotating in a spiral galaxy with a central hub where most of the matter is gathered. Since the centripetal force is due to gravity the orbital velocity of an object at a distance \(r\) from the centre is \([7]\):

\[
v(r) = \sqrt{\frac{GM(<r)}{r}} \tag{1.1}
\]

where \(M(<r)\) is the total mass within radius \(r\) and \(G\) is the gravitational constant. From Eq. (1.1), if the mass increases with radius, the velocity can increase or remain constant as

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\(^2\)In classical mechanics the virial theorem relates the average kinetic energy with the average of potential energy through the formula: \(<T> = -\frac{1}{2} <U>\)
function of $r$, with the exact behavior depending on the mass profile $M(r)^3$.

At a very large distance from galactic centre, where the density is expected to vanish and the amount of mass becomes constant, the orbital velocity will decrease as $\sqrt{r}$ (often referred to as *Keplerian behaviour*). What Rubin and collaborators found was a strong deviation from this expected behaviour. They observed that rotation curves are flat at large radii. This behaviour is shown in Figure 1.1. This suggests the presence of a considerable amount of non-luminous matter in a form of an halo that extends to large distances as depicted in Figure 1.2.

Indeed in the reference [9] fits of the observational data with the least square method for the dark halo hypothesis, for various galaxies, was carried out. These fits are well in agreement with experimental data. An example is shown in Figure 1.3, where also the rotation curves for the individual components of the galaxies, i.e. visible matter, gas and dark halo, were included.

### 1.1.2 Gravitational lensing

Another hint of the presence of the dark matter in the universe is provided by the *gravitational lensing*.

As we know from the Einstein’s General Theory of Relativity, the sources of the gravitational field, such as dark matter, affect not only the trajectory of a point mass or an extended massive object, but also the trajectory of a photon. In other words a bulk of mass can act as a gravitational lens that bends the light path [10].

It can be shown that the deflection angle $\alpha$ of photon passing near a point mass $M$ is:

$$\alpha = \frac{4GM}{c^2b}$$  \hspace{1cm} (1.2)

If the profile density is uniform one has $\rho = \text{unif} \Rightarrow M(r) \propto r^3 \Rightarrow v(r) \propto r$. On the other hand if $M \propto r \Rightarrow v = \text{const}$
where $b$ is the impact parameter of the scattering process of light by the gravitational field [11]. This deflection implies that a luminous body can appear in a distorted image when seen by an observer on the Earth. We can better understand this by looking at Figure 1.4. Assuming that we have a luminous body in $S$, an observer in $O$ and that the light rays emitted in $S$ pass near a point massive lensing object in $L$, having a mass equal to $M$. $D_{LS}$, $D_L$ and $D_S$ are the distances between the lensing object and the source, observer and the lens, the observer and the source, respectively. In the general case where the luminous source, the lensing mass and the observer are not on a straight line, two images of $S$ in $S_1$ and $S_2$ will appear.

From the Figure 1.4 we can write the geometric relation:

$$\alpha D_{LS} = D_s(\theta_1 - \theta_S)$$

Using the equation (1.2) we obtain:

$$\theta_S = \theta_1 - \left(\frac{4GM}{bc^2}\right)\left(\frac{D_{LS}}{D_S}\right) = \theta_1 - \left(\frac{4GM}{c^2}\right)\left(\frac{D_{LS}}{D_SD_L\theta_1}\right)$$ (1.3)

where at the first order approximation we have written:

$$b = D_L\theta_1$$
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Figure 1.4: The light rays emerging from the source $S$ are seen by the observer $O$ as coming from two different source points $S_1$ and $S_2$ because of the effect of the bending mass in $L$. The plane of view is that defined by $O$, $L$ and $S$.

If the source, the gravitational lens and the observer are on a straight line, $\theta_S = 0$, the Eq. (1.3) becomes:

$$\theta_1 = \theta_E = \left(\frac{4GM}{c^2 D_{LS}} \frac{D_{LS}}{D_S D_L}\right)^{1/2}$$  \hspace{1cm} (1.4)

In this case the image produced is a ring of light and $\theta_E$ is known as the *Einstein radius*. Thus it is possible to derive the gravitational potential, and therefore the mass, of the lensing object from the degree of deformation of the image observed. Comparing this mass with the luminous one it is possible to obtain the dark matter component of the gravitational lens.

Among the first ones to observe a gravitational lensing phenomenon in the 1979 were D. Walsh et al. [12]. With the 2.1 m telescope of the Kitt Peak National Observatory they found two quasar, labelled as 0957 + 561A and 0957 + 561B, separated by only $\sim 5.7$ arc second. These two objects exhibited almost identical spectra and redshift of $\sim 1.40$. At the end of the paper they considered that two objects were the same seen twice, due to the lensing effect of an intermediate massive objects.

In the Figure 1.5 it is reported an image of Abell 2218 galaxy cluster. It is an extraordinary example of gravitational lensing effect.

**Microlensing**

If the mass of the lensing object is very large, as occurs for galaxies and galaxy clusters, distinct and separated images of the source are produced due to the gravitational lensing. The same effect is not evident if the lens is of the typical stellar mass. In such a situation

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4Let us consider for example the situation in which the lensing object has a mass 10 times larger the solar one and that $D_{LS} = D_L = D_S/2 = 2pc$ - a typical interstellar distance. Inserting these values in the
a phenomenon known as microlensing may occur [14]. This phenomenon consists of an amplification of the source intensity as a function of time.

Starting from the equation (1.3) we obtain two solutions as:

$$\theta_{1,2} = \frac{\theta_s \pm \sqrt{\theta_s^2 + 4\theta_E^2}}{2} \quad (1.5)$$

These two solutions correspond to the angular positions of the two images. If the positions are too close to be resolved, an amplification of the signal occurs. The amplification will be the ratio of the solid angles $A = d\Omega/d\Omega_S = \theta/\theta_s \cdot d\theta/d\theta_S$. Thus for the single solution of (1.5) results:

$$A_{1,2} = \left| \frac{\frac{\theta_{1,2}}{\theta_s} \frac{d\theta_{1,2}}{d\theta_S}} \right| = \left| \frac{\theta_{1,2}^4 - \theta_E^4}{\theta_{1,2}^4 - \theta_E^4} \right|$$

If we now add the amplitudes from the two (unresolved) images, we obtain the net amplification of the (single) signal:

(1.4) we obtain an Einstein radius equal to $\theta_E \simeq 0.32\mu rad = 0.065$ arc sec. The resolution of one of the best telescopes, the Hubble, is 0.1 arc sec. Optical image of sources lensed by like-stars objects cannot be resolved.
where $u = \frac{\theta_*}{\theta_E}$.

When the lensing object moves between the observer and the source, the parameter $u$ depends on the time and the apparent intensity of the source will vary according to the variation of the net amplification (see equation (1.6)). If we consider the case of uniform motion, we can write $u(t)$ as:

$$u(t) = \sqrt{u_{\text{min}} - \left(\frac{t - t_0}{t_E}\right)^2}$$  (1.7)

where $u_{\text{min}}$ is the value of $u$ at the distance of closest approach, i.e. the smallest separation between the lens and the source in units of $\theta_E$, that occurs at time $t_0$ and $t_E = r_E/v_\perp = D_L\theta_E/v_\perp$ being $v_\perp$ the relative transverse velocity between the lens and the line of sight to the source. $t_E$ can be considered as the Einstein radius crossing time. Substituting (1.7) into the (1.6) we obtain the variation of the amplification with the time (see Figure 1.6).

Figure 1.6: Examples of the time dependence of the amplification for microlensing event for six values of the impact parameter $u_{\text{min}} = 0.0, 0.2, ... 1.0$, as labelled. Time is in units of the Einstein radius crossing time $r_E/v_\perp$. The inset illustrates the Einstein ring (dotted circle) and the source light ray paths relative to the lens (dot) for the six curves [15].

An important feature of these events distinguishing them from variable stars is that they show the same behavior of the amplification along the visible spectrum. This sort of
achromaticity can intuitively be explained as follows. A photon of momentum $p$ has an effective gravitational mass equal to $p/c^5$. In presence of a gravitational field it thus receives a transverse momentum $\Delta p \propto p$. Hence the deflection $\Delta p/p$ is independent of wavelength $\hbar/p$ (see Figure 1.7).

Figure 1.7: Amplification for red and blue light in a microlensing event. It is evident the similar behavior for the two components. The source is a star in the Large Magellanic Cloud, at a distance of 50 kpc [16].

The microlensing is a powerful tool to investigate the nature, ordinary or not, of the dark matter. In fact to explain dark matter some physicists hypothesized that it was composed by objects made of ordinary, baryonic matter, the so called MACHOs (Massive Compact Halo Object). This class of objects includes neutron stars, brown dwarfs, black holes and unassociated planets that would emit very little or no radiation. Searches for such objects was done by several collaborations using the microlensing effect towards the Large Magellanic Cloud [17, 18, 19]. In particular the MACHO Collaboration detected only 13-17 possible lensing event over 11.9 million stars studied. Thanks to this work, models with MACHOs accounting entirely for the presence of the dark matter in the universe are ruled out at 95% confidence level [17].

Even if the baryonic nature of dark matter is also ruled out by Big-Bang nucleosynthesis (BBN) there is surely an example of baryonic matter that is not affected by the BBN constraints: the primordial black holes [21]. It results that for some black hole masses it is

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5 A photon with momentum $p$ has an energy equal to $p \cdot c$. Since for a dimensional reason the energy have to be divided for $c^2$ we obtain that the effective gravitation mass of the photon is $p/c$.

6 The abundance of light elements predicted by BBN is linked to the baryon density and recent measurement constraint it to a value $\Omega_B = 0.04$ [20] that is too low for dark matter density as we will see later.
still possible that they account for the entire dark matter halo.

Cluster collisions

A further proof of the power of the gravitational lensing technique is provided by its application in galaxy cluster collisions events. Through the gravitational lensing it is possible to reconstruct the mass distributions of such events where mass to light ratios larger than 200 are measured.

![Figure 1.8: Left panel: The green lines depict the mass distribution of the cluster as gathered by means of gravitational lensing measurements; the blue crosses indicate the position of the center of the gas. Right panel: X-ray image of the plasma measured by Chandra, with the same green lines of the left panel. The white line in both panels sets the scale of 200 kpc.

Usually the largest component of baryonic matter in the clusters is represented by X-ray emitting intracluster gas in the form of plasma, whose mass exceeds that of the optically luminous matter by a factor $\sim 6$ [22]. So the location of X-ray radiation provide the position of the majority of baryonic matter, being the X-ray emission of the gas proportional to the square of its density [22]. During a cluster collision, the galaxies behave as collisionless particles while X-ray emitting intercluster plasma is subject to a slow down due to the high pressure of gas-gas and gas-dust interactions.

The surprising behavior observed in cluster collision events is that the mass distributions reconstructed by means of gravitational lensing is well separated from the X-ray radiation. This suggests that the majority of the matter is non-luminous, otherwise the gravitational potential reconstructed through the lensing would trace the plasma distribution. It is considered as one of the most convincing evidence for dark matter existence.

An extraordinary example of this is provided by the unique cluster 1E0657 – 558 [23] illustrated in Figure 1.8. The green lines depict the mass distribution of the cluster as retrieved by means of gravitational lensing measurements. In the right panel the X-ray radiation distribution observed by Chandra X-ray Observatory is shown. The discrepancy between the two distributions is evident.

In the reference [24] an extensive study of 72 cluster collisions was accomplished. The reconstructed gravitational centers appear always well separated from X-rays cloud, that is
the location of ordinary matter.

1.1.3 Cosmological evidences

Cosmic Microwave Background anisotropies

So far we have seen many phenomena that suggest the dark matter existence in the universe. Now it is essential to ask: what about the amount of dark matter in the universe? This information comes from the Cosmic Microwave Background (CMB). Discovered in the 1965 by Anzo Penzias and Robert Wilson \[25\] CMB carries information about global properties and composition of the universe. According to the Big Bang Theory it originated at the last scattering surface of photons when radiation decoupled by matter, approximately when universe was 400 000 years old \[26\]. In that epoch in fact, the expansion of the universe and the resulting cooling of the temperature allows the recombination of the electrons with the nuclei to form neutral atom. When this recombination took place, the photons were no more merged with charged particles due to interactions and were free to travel through the universe. The photons from the described “last scattering” are the ones responsible for the CMB. Due to the redshift of the radiation because of expansion and cooling of the universe, the spectrum of CMB is well described by a blackbody function with \( T = (2.7255 \pm 0.0006) \text{K} \) \[27\].

The CMB is isotropic to a high level. This means that at the epoch of recombination, when CMB was originated, the universe was rather homogeneous. However precise measurements of CMB show small anisotropy, at the \( 10^{-5} \) level (see Figure 1.9), which indicate little perturbations and are messengers of very important information about universe composition in its early age. In particular the CMB anisotropies can be divided in primary and secondary. The primary ones concern effects at the surface of last scattering and give us information about the time of radiation-matter decoupling and therefore provide indications about cosmological abundance of the primordial universe. The secondary anisotropies, instead, concern effects induced by the interaction of the CMB with matter. In other words the CMB photons we observe today have interacted with the matter along their path through the universe from the last scattering surface to us. So secondary anisotropies provide information about the abundance of the present epoch.

The first detection of these anisotropies was performed by the COBE satellite\[29\] and since that moment there has been an intense activity to survey the sky with an always better sensitivity and angular resolution as proved by the WMAP \[28\] and Planck Collaborations \[30\].

The CMB anisotropies are a function over a sphere, so it is natural to express them by using a spherical harmonics expansion:

\[
\frac{\delta T}{T_0}(\theta, \phi) = \sum_{l=2}^{+\infty} \sum_{m=-l}^{+l} a_{lm} Y_{lm}(\theta, \phi)
\] (1.8)

where the multipole coefficients \( a_{lm} \) are calculated from:
Figure 1.9: Cosmic microwave background according to WMAP 5-year results [28]. With the support of the scale at the bottom fluctuations of very small magnitude are evident, around the average temperature measured to be $T = (2.7255 \pm 0.0006)$ K.

$$a_{lm} = \int Y_{lm}^* (\theta, \phi) \frac{\delta T}{T_0} (\theta, \phi) d\Omega \quad (1.9)$$

The definition given in Eq. (1.8) provide dimensionless multipole coefficients $a_{lm}$. Often they are defined without the ratio with $T_0 = 2.7255$ K, so the $a_{lm}$ have the dimension of a temperature and are given in units of $\mu$K. It is worth underlining that the sum over $l$ in Eq. (1.8) starts from $l = 2$. This is because the largest anisotropy contribution from $l = 1$ (dipole) is a frame dependent contribution which arises from our peculiar motion with respect to the CMB rest frame [31]. So we can determine the absolute rest frame as that in which the CMB dipole would be zero. So we subtract the dipole contribution from Eq. (1.8).

The very important quantity are the variances $C_l$ of the $a_{lm}$ coefficients that contain the largest majority of cosmological information. Thus we define:

$$C_l \equiv \langle |a_{lm}|^2 \rangle = \frac{1}{2l + 1} \sum_m |a_{lm}|^2 \quad (1.10)$$

The function $C_l$ is called angular power spectrum. Being the different multipole coefficients independent random variables, it results:

$$\langle a_{lm} a_{l'm'}^* \rangle = \delta_{ll'} \delta_{mm'} C_l \quad (1.11)$$
As a matter of fact, the power spectrum is a complete representation of the data only if the $a_{lm}$ multipole coefficients, and hence the CMB anisotropy are Gaussian [32]. Various tests confirm that if there is any non Gaussian contribution, it would be one or two order of magnitudes below the current observational limits [33]. Thus fitting the angular power spectrum extracted from the observed CMB with theoretical models, very important cosmological information, among which universe matter-energy composition, can be obtained.

The angular power spectrum is related to the temperature variance through:

$$\left\langle \frac{(\delta T(\theta, \phi))^2}{T} \right\rangle = \left\langle \sum_{lm} a_{lm} Y_{lm}(\theta, \phi) \sum_{l'm'} a_{l'm'}^* Y_{l'm'}^*(\theta, \phi) \right\rangle$$

$$= \sum_{ll'} \sum_{mm'} Y_{lm}(\theta, \phi) Y_{l'm'}^*(\theta, \phi) \langle a_{lm} a_{l'm'}^* \rangle$$

$$= \sum_{l} C_l \sum_{m} |Y_{lm}(\theta, \phi)|^2 = \sum_{l} \frac{2l + 1}{4\pi} C_l$$

(1.12)

where have been used Eq. (1.11) and the property of spherical harmonics:

$$\sum_{m} |Y_{lm}(\theta, \phi)|^2 = \frac{2l + 1}{4\pi}$$

Thus if we have a plot of the function $(2l + 1)C_l/4\pi$ on a linear scale, or of the function $l(2l+1)C_l/4\pi$ on a logarithmic scale, the area under the curve gives the temperature variance. Often in place of the previous two choices the angular power spectrum is plotted as $l(l+1)C_l/2\pi$. The reason is that the Sachs-Wolfe [7] part of angular power spectrum is flat under some conditions [34].

The angular power spectrum can be evaluated by a six parameters model. The parameters are [35]:

- total matter density, $\Omega_m h^2$;
- baryonic matter density, $\Omega_b h^2$;
- Hubble constant, $H_0$;
- amplitude of fluctuations, $\sigma_8$;
- optical depth, $\tau$;
- slope for the scalar perturbation spectrum, $n_s$;

---

7The Sachs-Wolfe effect is one of the intereactions that generate the CMB anisotropy. It is a gravitational effect due to the presence of density perturbation at the last scattering surface.

8Anyway this effect is easily visible only if the multipole axis is logarithmic.
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From some of these parameters also information about *dark energy* content of the universe can be obtained. This cosmological standard model used to describe the CMB anisotropies and to fit the data is called ΛCDM (Λ Cold dark matter). Here Λ refers to the cosmological constant, that is also in the Einstein’s equation of general relativity, necessary to explain the current accelerated expansion of the universe and is associated to the dark energy. The expression “Cold dark matter” refers to an important property of dark matter particles: their slow speed. This property excludes “hot” dark matter candidates, i.e. dark matter particle with relativistic dispersion velocity.

![Figure 1.10: The theoretical CMB anisotropy power spectrum, using a standard ΛCDM model from CMBFAST. The x-axis is in logarithmic scale. The main effects that generate the CMB anisotropies are labelled: the ISW (Integrated Sachs-Wolfe) rise; Sachs-Wolfe plateau; acoustic peaks; and damping tail. Also shown is the shape of the tensor (gravitational wave) contribution (by inflation theory), with an arbitrary normalization.](image)

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Figure 1.10 depicts the CMB anisotropies as described by the ΛCDM model. The regions containing most of the CMB angular spectrum are labeled. Among these we highlight acoustic peaks. Before the decoupling between baryons, essentially protons, and photons, they can be modeled as a photon-baryon fluid. These peaks are due to the oscillation of the photon-baryon fluid due to the dark matter-dominated gravitation potential compressing the fluid and the radiation pressure pulling the fluid out. From the relative height of the acoustic peaks the fraction of baryonic matter and the total matter density can be estimated. This allows also calculating the total dark matter density. Results from reference [36] show...
a flat universe with $\Omega_{CDM} = 0.265$, $\Omega_b = 0.049$ and $\Omega_\Lambda = 0.686$. Figure 1.11 shows data from various experiments of the angular power spectrum together with a best fit of Planck Collaboration.

![Figure 1.11: CMB temperature anisotropy band-power estimates from the Planck, WMAP, ACT, and SPT experiments. Note that the widths of the $l$-bands vary between experiments and have not been plotted. This figure represents only a selection of the most recent available experimental results, and some points with large error bars have been omitted. The x-axis here is logarithmic for the lowest multipoles, to show the Sachs-Wolfe plateau, and then linear. The acoustic peaks and damping region are visible clearly. The plotted curve is the best-fit Planck model.][34].

Big Bang Nucleosynthesis

Big Bang Nucleosynthesis (BBN) refers to a period in the early universe, from a few seconds to a few minutes after the Big Bang, when the high temperature allowed the nuclear fusion between neutrons and protons to form deuterium, helium, and small amounts of lithium and other light elements. By comparing the abundance of these primordial elements predicted by the Big Bang theory to that derived from observations, it is possible to estimate the total baryonic content of the universe.

In particular it is customary to look at deuterium abundance. In fact since the deuterium produced in the stars is almost immediately converted into $^4\text{He}$, the BBN results to be the
largest source of deuterium in the universe. Thus, the abundance of deuterium we observe today can be considered as a lower limit of the amount of the same nucleus created by the Big Bang. For this reason, measuring the deuterium to hydrogen ratio $D/H$ at distant regions where there is a small amount of elements heavier than lithium it is possible to estimate the $D/H$ ratio directly after BBN. In fact the small amount of elements heavier than lithium is an indication that the observed regions have not changed significantly since the Big Bang. Through nuclear physics and known reaction rates, BBN abundance can be theoretically estimated. This computed abundance results to be dependent on the baryon density. Figure 1.12 shows the experimentally observed and computed abundances of specific elements versus the baryon density. The horizontal bands indicate the experimentally observed abundance and the curves indicate the theoretical predictions from BBN. The vertical line indicate the baryon density obtained by recent precision measurements [38]. Note the high precision within the theoretical and observational errors of the Big Bang Nucleosynthesis: the vertical strip fits the four abundance simultaneously.

R. H. Cyburt calculated two possible values for $\Omega_b h^2$ depending on which deuterium observation is considered [39]. In his work Cyburt considered two observational values of the deuterium abundance, in turn borrowed by the work of Kirkman et al. [40]. Thus the values found by Cyburt are:

$$\Omega_b h^2 = 0.0229 \pm 0.0013$$
\[ \Omega_b h^2 = 0.0216^{+0.0020}_{-0.0021} \]

Both values are very far from the total matter density \( \Omega_m = 0.315 \pm 0.017 \) where \( h = 0.673 \pm 0.012 \). This implies that most of matter is of non-baryonic kind.

### 1.2 Dark matter candidates

As we have already seen, dark matter candidates have to be cold, and therefore non-relativistic. A confirmation comes also from the cosmological simulations of structures formation. First of all the so-called N-body simulations confirm the need for the dark matter in order to reproduce the observed large scale structures, such as galaxy filaments and galactic voids [1]. In addition, these simulations confirm that dark matter must be cold, so that the accepted bottom-up formation takes place. According to the bottom-up progression, the formation of smaller scale structure like galaxies followed by bigger structures like galaxy cluster occurred. On the contrary, hot dark matter implies a top-down formation. This constraints dark matter candidates and rules out the left-handed neutrino together with his anti-particle the right-handed antineutrino, the only of Standard Model (SM) candidate.

We now list in short some of the most interesting dark matter candidates, referring to [7] and [41] for a complete review of the possible DM candidates. Weakly Interactive Massive Particle (WIMP) will be discussed in the next paragraph.

Introduced in theories that extend the SM to explain the smallness of neutrino masses and therefore fix the hierarchy problem [42], sterile neutrinos provide a possible dark matter candidate. Proposed as dark matter candidates in 1993 by Dodelson and Widrow [43] they would constitute cold or warm \(^9\) dark matter particle according to the mechanism responsible for their production [44]. An indication for the presence of such particles could come from the X-ray measurement from the sterile neutrino decay via the radiative channel: \( N \rightarrow \nu \gamma \). Search for lines in the X-ray spectrum are ongoing.

The axion was implicitly included in the Peccei-Quinn theory, formulated to explain why strong interactions do not violate the CP symmetry [45]. In fact there is no fundamental reason for the Quantum Chromodynamics (QCD) to conserve CP. To solve this problem Peccei and Quinn introduced a new U(1) global symmetry. Later Wilczeck noticed that the Peccei-Quinn theory entailed the existence of a neutral and stable pseudoscalar boson that was called axion [46]. This particle can represent a DM candidate and could account for the complete dark matter content of the universe [47]. It is expected that the axion couples to photons, therefore some of the experiments aiming at its detection use tuned radio frequency cavities: thanks to the strong magnetic field of the cavity, the axion can be converted in photons and can be seen as an excess power in the cavity [1].

Among other exotic candidates we remind Lightest Kaluza-Klein particles [48] and WIMP-Pzillas postulated to explain the origin of ultra high energy cosmic rays [49].

\(^9\)A warm dark matter particle refers candidates with relativistic velocity only in an early epoch, so they are between cold and hot DM.
1.3 Thermal relic density

Before talking about the WIMPs it is important to estimate the density of the DM particles with the aim of comparing this value with the observed one. This can help eventually to rule out some possible candidates.

It is widely accepted that energetic and massive particles were in equilibrium with the thermal plasma when they were produced. This means that the annihilation rate of a given particle was equal to the production rate in the early universe. As the universe expanded and the temperature of the plasma decreased, lighter particles had no more sufficient kinetic energy (thermal energy) to create heavier particles. Thus the conditions for thermal equilibrium were violated at some point. Furthermore with the expansion of the universe also the annihilation rate of the given particle decreases. When the annihilation rate becomes smaller than the Hubble expansion rate the particle freezes out. The density of a specific particle at the freeze-out is called relic density. From this instant its abundance remains constant. The relic density can be theoretically calculated so it is essential that a given DM candidate has the given relic density in agreement with the reported abundance indicated in section 1.1.3.

It can be shown that the density of a given particle, under some conditions, evolves with time according to the following equation [50]:

\[
\frac{dn}{dt} = -3Hn - \langle \sigma_{\text{ann}}v \rangle (n^2 - n_{eq}^2)
\] (1.13)

where \( n \) is the density of the particle, \( H \) is the Hubble expansion rate, \( \langle \sigma_{\text{ann}}v \rangle \) is the thermally averaged total cross section for annihilation of a particle with its anti-particle times the relative velocity of the two particles in the center of mass frame; \( n_{eq} \) is the equilibrium thermal density.

Although no closed-form analytic solution of Eq. (1.13) exists, we now indicate an analytic approximation that yields a solution, for annihilation cross section, that can be considered rather independent on the energy, with an accuracy of about 10% [50]:

\[
\Omega_{\text{cdm}}h^2 = \frac{m_\chi n_\chi}{\rho_c} \approx 3 \cdot 10^{-27} \text{cm}^3\text{s}^{-1}
\] (1.14)

where \( \chi \) is a generic dark matter particle.

This result shows that the dark matter density in units of the critical density, is independent from the mass of the possible DM candidate except for logarithmic corrections.

1.4 WIMP

Among the most compelling DM candidates surely there is the Weakly Interactive Massive Particle (WIMP). Not included in the Standard Model, it is a particle that would be stable, neutral, with masses from below GeV/c\(^2\) to several TeV/c\(^2\) and it could account entirely for the dark matter amount. The reason why WIMPs are considered as reasonable particles
lies in Eq. (1.14). In fact if a new particle with weak scale interactions exists, it can be estimate to have an annihilation cross section times speed \( \langle \sigma_{\text{ann}} v \rangle = 10^{-25} \text{cm}^3 \text{s}^{-1} \). This value provides a relic density close to the right abundance of dark matter reported.

The identity of the WIMP remains a mystery but surely the best motivated and theoretically developed WIMP candidate comes from Supersymmetry (SUSY) (for a complete and not hard treatment of Supersymmetry see [51]). In particular when we talk about SUSY in this context we refer to the Minimal Supersymmetric Standard Model (MSSM) which is an extension of the SM involving Supersymmetry. The MSSM establishes that each particles of the SM has a supersymmetric partner that differs of 1/2 unity of spin. In other words every fermion has a bosonic partner with identical quantum numbers and vice-versa. If SUSY was an exact symmetry each pair of partner particles would have exactly the same mass. Since this is not observed, SUSY is considered a broken symmetry. Due to this breaking symmetry all superpartners have to be highly massive, but no too much otherwise we would lose the cure for the hierarchy problem that is one of the reasons why SUSY was developed [51].

Since heavier SUSY particles would decay to lighter ones, the WIMP candidate would be the lightest supersymmetric particle (LSP). Being the LSP however a massive particle, a new symmetry was introduced to preserve it from decaying to lighter ordinary particles of the SM: the so called R-parity. It is a multiplicative quantum number and it is assumed to be conserved. The quantum number \( R \) is defined as:

\[
R = (-1)^{3(B-L)+2s}
\]

where \( B \) and \( L \) are the baryonic and leptonic numbers, respectively, while \( s \) is the spin. It can be shown that \( R = 1 \) for all the ordinary particle of the SM while \( R = -1 \) for their supersymmetric partners (sparticle). This have crucial implications:

- in a process initiated by particles, the sparticles can be produced only in pairs. This is important for collider experiments that involve dark matter search;
- each sparticle different from LSP, must eventually decay into a state that contains an odd number of LSPs (usually just one).
- LSP must be stable. This is needed for a LSP to be a WIMP candidate.

The most accepted LSP is the so-called neutralino \(^{10}\). This particle, usually indicated with \( \chi \), is a linear combination of two higgsinos, the photino and the zino [50]

\[
\chi = C_1 \tilde{B} + C_2 \tilde{W}^3 + C_3 \tilde{H}_1 + C_4 \tilde{H}_2
\]  

(1.15)

where \( \tilde{B} \) and \( \tilde{W}_3 \) are the supersymmetric partners of the \( U(1)_Y \) symmetry group gauge field \( B \) and the third component of the \( SU(2) \) gauge field \( W^3 \), that mix to make the photon and \( Z \). Depending on the values assumed by the coefficients in Eq. (1.15), the neutralino

\(^{10}\)Often also the sneutrino is considered as a viable LSP candidate, but there are cosmological reasons against a stable sneutrino. Moreover it was showed that most of the regions of sneutrino parameters space are ruled out by DM direct-detection experiments [52]
can go from a state of a nearly pure bino to a nearly pure higgsino. It coincides with the own antiparticle.

Thus the $\chi\chi$ annihilation in particles of the Standard Model can be a way to indirectly detect WIMPs.
Chapter 2

WIMP direct detection and NEWSdm experiment

This chapter is devoted to the illustration of general principles of WIMP direct detection and to the description of the NEWSdm (Nuclear Emulsion for WIMP Search with directional measurement) experiment, subject of the present thesis.

2.1 Dark matter detection

We have seen in the previous chapter that there are compelling evidences about the presence of dark matter in the universe. Three scenarios can be pursued to test DM hypothesis as illustrated in Figure 2.1: (i) production of DM at particle accelerators by means of ordinary particles collision, (ii) indirect detection by searching for signal from annihilation products and (iii) direct detection of DM scattering off target nuclei.

Dark matter search at accelerators is currently being performed at the Large Hadron Collider (LHC) at CERN with ATLAS [53] and CMS [54] experiments. They aim at detecting events with missing transferred momentum and energy, thus deducing the presence of DM. So far no deviations form standard model expectations have been observed [55, 56]. In the context of DM search with accelerators it is worth mentioning the SHiP (Search for Hidden Particles) project. An experiment proposal at the CERN SPS, aiming at detection of dark matter produced directly in proton collision in the target, or by the dark photon [57, 58].

The dark photon is a vectorial boson that would be able to couple with ordinary matter. In principle each process that involves a photon could involve also a dark photon. The reason why it has not been detected yet is because of its very weak coupling with ordinary matter and the ordinary photon. Dark photon obtained a great interest because it could explain the PAMELA discrepancy of the $e^+$ to $(e^+ + e^-)$ flux ratio respect to the expected one [59] (while no discrepancy was recorded for the antiproton fraction [60]), as we will see, and the discrepancy of the measured anomalous magnetic moment with respect to the one predicted by the SM[61].

In indirect detection experiments the WIMPs particles are searched for through the
Figure 2.1: Scheme of the possible scenarios to test dark matter hypothesis: production at colliders $PP \rightarrow \chi\chi$, indirect detection $\chi\chi \rightarrow PP$ through their annihilation and direct detection $\chi P \rightarrow \chi P$.

Detection of their annihilation products. Since the neutralino coincides with its anti-particle, it can annihilate producing photons, neutrinos and anti-matter particles. Since the WIMP annihilation rate is proportional to the square of the dark matter density, indirect detection is performed mainly in high WIMP density region [62], such as galactic centre and halo, close galaxy cluster or dwarf galaxies and sun.

Being neutral, $\gamma$-rays and neutrinos would point to the source where they were produced, although $\gamma$-rays can be absorbed in the interstellar medium. Thus many efforts have been made to measure such particles. It is worth mentioning EGRET [63] [64], HESS [65] and Fermi-LAT [66] as far as the detection of dark matter signals from $\gamma$-rays measurements is concerned and the experiments Ice Cube [67], ANTARES [68] and Super-Kamiokande for the detection of dark matter signals from neutrino measurements. Encouraging results come from the EGRET Collaboration, which in 1998 reported an excess of $\gamma$-rays [64]. However EGRET’s results remain controversial. Any model based on dark matter annihilation into quark jets, such as the supersymmetric model also predicts a primary flux of antiprotons from the same jets. In reference [70] it is shown that the antiproton fluxes would be much larger if the excess of $\gamma$ rays was due to neutralino annihilation.

Since the antimatter cosmic flux is very low, a possible excess would be a ”smoking gun” of WIMP presence. An excess of positron fraction in the energy range 10 GeV to $\sim 250$ GeV was reported by Pamela collaboration [59] and later confirmed by AMS [71]. However to explain this excess some ordinary hypotheses such as production by the pulsar or by the collision of cosmic rays with interstellar matter cannot be excluded [72].

In the next section we report DM direct detection.
2.2 Dark matter direct detection

An unambiguous proof of the WIMP hypothesis would be its direct detection, through elastic scattering off nuclei $\chi N \rightarrow \chi N$. Thus WIMP direct detection requires the observation of DM-induced nuclear recoil tracks.

Being a basic ingredient for the event rate of WIMP direct detection experiments, we describe the WIMP velocity distribution with respect to the Earth and its density distribution. Then we discuss the general principles of direct detection.

2.2.1 WIMP halo properties

Available data on the structure of the Milky Way do not provide strong constrains on the dark matter halo density profile. However the following phenomenological form for the dark matter halo density is usually adopted \[ \rho(r) = \frac{\rho_0}{\left(\frac{r}{r_s}\right)^\gamma \left[1 + \left(\frac{r}{r_s}\right)^\alpha\right]^{\frac{\beta - \gamma}{\alpha}}} \] (2.1)

where $r_s$ is the scale radius, a parameter related to the core radius of the halo, $\rho_0$ is the central density, $\alpha$, $\beta$ and $\gamma$ are free parameters that are retrieved by fitting rotation curves. In the table 2.1 the values of the parameters for some of the most used density profile are showed: the Navarro-Frenk-White model [74], the model we call $K_1$ and $K_2$ described by Kravtsov et al., introduced to reproduce the rotation curves of a sample of dark matter-dominated dwarf and low surface brightness late-type galaxies [75] and the isothermal profile.

<table>
<thead>
<tr>
<th>Profile</th>
<th>$\alpha$</th>
<th>$\beta$</th>
<th>$\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NFW</td>
<td>1</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>$K_1$</td>
<td>2</td>
<td>3</td>
<td>0.2</td>
</tr>
<tr>
<td>$K_2$</td>
<td>2</td>
<td>3</td>
<td>0.4</td>
</tr>
<tr>
<td>Isothermal</td>
<td>2</td>
<td>2</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 2.1: Values of the parameters for some halo density profile models described by Eq. (2.1).

The cited profiles are all capable to reproduce rotation curves of most galaxies over a wide range of radii, but are not in agreement with observed data at very small and very large radii.

In this work an isothermal profile is assumed, i.e. a spherically symmetric profile of the following form:

\[ \rho(r) = \frac{\rho_0}{1 + \left(\frac{r}{r_s}\right)^2} \] (2.2)
One of the most important parameters for determining the expected event rate for a direct detection experiment is the local dark matter density. It is common to assume a value of 0.3 GeV/cm$^3$ [26], anyway depending on the profile model used for the halo, $\rho_0$ can vary in the range $(0.2 - 0.4)$ GeV/cm$^3$ [76].

The dark matter velocity profile is usually assumed to be described by an isotropic Maxwell-Boltzmann distribution$^1$[77]:

$$f(v) = 4\pi \sqrt{\left(\frac{3}{2\pi \sigma^2}\right)^3} v^2 \exp\left[-\frac{3v^2}{2\sigma^2}\right]$$  \hspace{1cm} (2.3)

where $\sigma$ is the velocity dispersion and is related to the local circular velocity via $\sigma = v_c \sqrt{3/2}$. A commonly used value for $v_c$ is $v_c \sim 220$ km/s. The mean velocity results to be $\langle v \rangle = 2v_c/\sqrt{\pi}$.

The distribution (2.3) is truncated at the galactic escape velocity in order to take into account that the Milk Way halo is finite and thus the particle with speed larger than the escape one are not gravitationally bound to the Milk Way. There are large uncertainties about the value of the galactic escape velocity with a range of possible values in the interval $(498 - 608)$ km/s [78]. The commonly used value is 544 km/s as reported in the same paper.

It is useful to transform the WIMP velocity distribution from Galactic rest frame to the laboratory frame. Indicating with $v$ the WIMP velocity in the Galactic frame, with $v'$ the WIMP velocity in the laboratory frame (corresponding to the Earth) and with $v_E$ the motion of the Earth respect to the Galactic rest frame we can write the transformation:

$$v = v' + v_E$$  \hspace{1cm} (2.4)

In turn the Earth motion relative to the Galactic rest frame can be expressed as the sum of three components[79]

$$v_E = u_r + u_S + u_E$$  \hspace{1cm} (2.5)

where $u_r$ is the velocity of the Local Standard of Rest (LSR) that in galactic coordinates is:

$$u_r = (0, v_c, 0) \text{ km s}^{-1}$$  \hspace{1cm} (2.6)

being $v_c$ the local circular speed, $u_S$ is the Sun velocity relative to the LSR, whose determination given in [80] provides the values:

$$u_S = (11.1, 12.2, 7.3) \text{ km s}^{-1}$$  \hspace{1cm} (2.7)

and $u_E$ is the Earth’s orbital velocity relative to the Sun, given by:

$^1$This is reasonable if we consider an halo profile that is an isotropic and isothermal sphere, and if we consider the collisionless nature of dark matter particles.
\[ \mathbf{u}_E = u_E(\lambda) (\cos \beta_x \sin(\lambda - \lambda_x), \cos \beta_y \sin(\lambda - \lambda_y), \cos \beta_z \sin(\lambda - \lambda_z)) \] (2.8)

where \( \beta \) and \( \lambda \) are the ecliptic latitudes and longitudes respectively of \( x, y \) and \( z \) axis in galactic coordinates and

\[ u_E(\lambda) = \langle u_e \rangle [1 - e \sin(\lambda - \lambda_o)] \] (2.9)

being \( \langle u_e \rangle \) the Earth’s mean orbital velocity, \( e \) the ellipticity of the Earth’s orbit and \( \lambda_o \) the longitude of the orbit’s minor axis.

A good approximation\textsuperscript{[79]} of \( v_E \) is:

\[ v_E = 244 + 15 \sin(2\pi y) \text{ km s}^{-1} \] (2.10)

where \( y \) is the elapsed time from March 2\textsuperscript{nd}, in years. Thus, generally, is fundamental to take into account also the velocity around the Earth axis that determines a daily modulation of the WIMP velocity. Figure 2.2 illustrates the Earth’s motion with respect to the Galactic rest frame.

![Figure 2.2: Representation of the Earth’s motion with respect to the Galactic rest frame.](image)

### 2.2.2 Principles of direct search

The aim of WIMP direct detection is to observe nuclear recoils produced in WIMP-nucleus elastic scattering. The energies of the recoiling nuclei are expected to be in the range \((1 - 100) \text{ keV}\) for WIMPs mass of \((10 - 100) \text{ GeV}/c^2\) \textsuperscript{[79]}. 
Elastic cross section

WIMPs are expected to be non relativistic Majorana particles. For such particles two cases can be considered: the spin-independent and spin-dependent cross-section [50]. In the former case, WIMPs couple to the mass of nucleus and the scattering results to be a coherent process as the scattering amplitude of each nucleon adds in phase. The latter exists only if the WIMP has a spin different from zero and describes the case where the WIMP couples to the nuclear spin and only unpaired nucleons contribute to the scattering. Therefore only targets composed by nuclei with an odd number of protons or neutrons are sensitive to spin-dependent interactions.

For spin-dependent interactions the differential cross section with respect the transferred momentum $q$ can in general be expressed as [50]

$$\frac{d\sigma^{SD}}{d|q|^2} = \frac{\sigma_0^{SD}}{4m_r^2v^2} F^2(|q|)$$  \hspace{1cm} (2.11)

where the transferred momentum is equal to $q = m_r v$ being $m_r = m_A m_\chi/(m_A + m_\chi)$ the reduced mass of the system made by the WIMP and the nucleus with mass $m_A$ and $v$ is the WIMP velocity relative to the target. $F^2(|q|)$ is the form factor that is written in terms of spin structure function as

$$F^2(|q|) = \frac{S(|q|)}{S(0)}$$  \hspace{1cm} (2.12)

and is normalized so that $F(0) = 1$ and $\sigma_0^{SD}$ is the total cross section at zero momentum transfer:

$$\sigma_0^{SD} = \frac{32}{\pi} G_F^2 m_r^2 \Lambda^2 J(j + 1)$$  \hspace{1cm} (2.13)

being $G_F$ the Fermi coupling constant, $J$ the total angular momentum of the nucleus and $\Lambda$ is given by:

$$\Lambda = \frac{1}{J} [a_p \cdot \langle S^p \rangle + a_n \cdot \langle S^n \rangle]$$  \hspace{1cm} (2.14)

Here $\langle S^p,n \rangle$ denotes the expectation value of the nuclear spin due to the proton and neutron system, and $a_{p,n}$ are the axial couplings.

The spin-independent elastic scattering cross section can be expressed as [50]:

$$\frac{d\sigma^{SI}}{d|q|^2} = \frac{\sigma_0^{SI}}{4m_r^2v^2} F^2(Q)$$  \hspace{1cm} (2.15)

where the form factor $F(Q)$ is written as a function of the energy transferred from the WIMP to the nucleus ($Q$). Commonly the Helm parameterisation [81] is used for the form factor. For spin-independent elastic scattering the cross section at zero momentum transfer is:
CHAPTER 2. WIMP DIRECT DETECTION AND NEWSDM EXPERIMENT

\[ \sigma_0^{SI} = \frac{4m_r^2}{\pi} [Z \cdot f_p + (A - Z) \cdot f_n]^2 \] (2.16)

where \( Z \) is the atomic number and \( (A - Z) \) is the number of neutrons of the target nucleus, while \( f_p, f_n \) are the effective couplings of the WIMP to the protons and neutrons. Often, \( f_p \approx f_n \) is assumed and the cross section is proportional to \( A^2 \).

Event rate and experimental signatures of WIMP

Direct detection experiments measure the event rate of WIMP interactions, usually expressed per unit mass of detector material. In general this event rate is given by:

\[ R = \frac{n\sigma(v)}{m_A} \] (2.17)

where \( \sigma \) is the elastic scattering cross section of the WIMPs and \( n = \rho_0/m_\chi \) is the WIMP density, being \( \rho_0 \) the local dark matter density. \( \sigma \) and \( m_\chi \) are the observables in dark matter experiments. \( \langle v \rangle \) is the average speed of the WIMPs relative to the target and the mass detector \( M_{det} \) (assumed to be unitary) is divided by the target nucleus mass \( m_A \) to get the number of target nuclei.

More accurately, one should take into account that the WIMPs have a velocity distribution \( f(v) \) with respect to the halo and that the differential cross section depends on \( f(v) \). Moreover one has to consider that the detectors have an energy threshold \( E_T \), below which they are insensitive to the WIMP-induced nuclear recoils. In addition, the Earth moves through the Galactic halo and this motion should be taken into account via \( f(v) \).

Thus the differential rate per unit detector mass can be written as:

\[ dR = \frac{\rho_0}{m_\chi m_A} v f(v) \frac{d\sigma}{d|q|^2} d|q|^2 dv \] (2.18)

The velocity distribution in Eq. (2.18) corresponds to the distribution of the velocity relative to the detector, therefore it is equal to Eq. (2.3) after the application of the Galilean transformation (2.4). For the elastic scattering the transferred momentum is \( |q|^2 = 2m_r^2v^2(1 - \cos \theta^*) \) where \( \theta^* \) is the scattering angle in the center of mass frame and \( m_r = m_\chi m_A/(m_\chi + m_A) \) is the reduced mass of WIMP-nucleus system. From this expression we can write the energy deposited in the detector as:

\[ Q = \frac{|q|^2}{2m_A} = \frac{m_r^2v^2}{m_A}(1 - \cos \theta^*) \] (2.19)

Thus from the equations (2.18), (2.19) and (2.11) or (2.15) for the spin-dependent and spin independent elastic scattering processes, we can get the differential recoil spectrum for the interactions of the dark matter in the target:

\[ \frac{dR}{dQ} = \frac{\sigma_0 \rho_0}{2m_\chi m_r^2} F^2(Q) \int_{v_{min}}^{v_{max}} \frac{f(v)}{v} dv \] (2.20)
where the integration is performed over all possible incoming velocities. \( v_{\text{min}} \) is the minimum velocity of the WIMP that can give a recoil energy \( Q \). It is given by:

\[
v_{\text{min}} = \sqrt{\frac{Q m_A}{2 m_r^2}} \tag{2.21}
\]

while \( v_{\text{max}} \) is the escape velocity of the WIMPs in the halo\textsuperscript{[79].}

To make the calculations more straightforward we can define the following dimensionless quantity:

\[
T(Q) = \frac{\sqrt{\pi}}{2} v_c \int_{v_{\text{min}}}^{v_{\text{max}}} \frac{f(v)}{v} dv \tag{2.22}
\]

where \( v_c \) is the local circular velocity, already present in equations (2.3) and (2.6). The differential recoil spectrum can be factorized in a form-factor part and a part that depends upon WIMP velocity:

\[
dR \frac{dQ}{dQ} = \frac{\sigma_0 \rho_0}{v_c m_x m_r^2 \sqrt{\pi}} F^2(Q) T(Q) \tag{2.23}
\]

Finally it is possible to write the total event rate per kilogram of active material of detector per day as:

\[
R = \int_Q^\infty dQ \frac{dR}{dQ} \tag{2.24}
\]

being \( E_T \) the the energy threshold of the detector.

For a velocity distribution as that given in Eq. (2.3), Eq. (2.22) gives simply:

\[
T(Q) = \exp \left( - \frac{v_{\text{min}}^2}{v_c^2} \right) \tag{2.25}
\]

having taken into account that \( \sigma \) in the Eq. (2.3) is equal to \( \sigma = v_c \sqrt{3/2} \). If we consider light WIMP where \( F(Q) \approx 1^2 \), the differential recoil spectrum is:

\[
dR \frac{dQ}{dQ} = \frac{\sigma_0 \rho_0}{m_x m_r^2 v_c \sqrt{\pi}} \exp \left( - \frac{Q m_A}{2 m_r^2 v_c^2} \right) \tag{2.26}
\]

where Eq. (2.21) has been used. Integrating over the energy to get the total rate one obtains:

\[
R = \frac{\sigma_0 \rho_0}{m_x m_A \sqrt{\pi}} 2 v_c \exp \left( - \frac{E_T m_A}{2 m_r^2 v_c^2} \right) \tag{2.27}
\]

Notice that with \( E_T = 0 \) this result corresponds to the naive result given by Eq. (2.17), since for the speed distribution (2.3) \( \langle v \rangle = 2 v_c / \sqrt{\pi} \).

\textsuperscript{2}For light WIMP the transferred momentum is in general smaller, hence the wavelength \( h/|q| \) is in a good approximation large with respect to the nuclear radius that is seen by the WIMP as a point-like particle.
These results are obtained without including the transformation (2.4) in the Eq. (2.3). If this transformation is considered one obtains [50]:

$$\frac{dR}{dQ} = \sigma_0 \rho_0 \frac{E^2(Q)}{4v_E m_X m_r^2} \left[ \text{erf} \left( \frac{v_{\text{min}} + v_e}{v_c} \right) - \text{erf} \left( \frac{v_{\text{min}} - v_e}{v_c} \right) \right]$$

(2.28)

where erf is the error function:

$$\text{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt$$

When the expression (2.10) is used for the Earth’s velocity a modulation effect appears in the rate. The $\sim 6\%$ modulation in (2.10) gives rise only to a $\sim 3\%$ modulation in rate [79].

Finally it is worth outlining that since the WIMP flux in the lab frame is peaked in the direction of motion of the Sun, a very important feature of the dark matter signal is the directionality. In fact the direction of the nuclear recoils induced by the WIMPs results to have a strong angular dependence. The directional dependence results to be more striking than the seasonal modulation [82]. The angular dependence is evident if one writes the differential rate as a function of the angle $\gamma$, defined as the direction of the nuclear recoil with respect to the direction of the solar motion [83]:

$$\frac{d^2R}{dE d\gamma} \propto \exp \left[ - \left( \frac{(v_E^p + v_e) \cos \gamma - v_{\text{min}}}{v_c} \right)^2 \right]$$

(2.29)

where $v_{\text{min}}$ is one used in (2.21), $v_c$ is the local circular velocity and $v_E^p$ is the component of the Earth’s velocity parallel to the direction of Solar motion. The integrated rate of scattering events in the forward direction is expected to exceed the rate for backwards scattering event by one order of magnitude.

### 2.2.3 Generic result of a direct detection experiment

The results of a direct detection experiment for WIMP search are commonly reported in the (WIMP-nucleon cross-section, WIMP mass) plane. This is illustrated in Figure 2.3. Generic upper limit (the open black curve) in the WIMP cross section versus the WIMP mass are reported, that refers to the case in which no evidence of the signal is found and delimits the region of parameter space that is excluded by the experiment. Also a contour region (closed black line) indicating a possible DM detection is plotted, that refers to the case in which evidence for the signal is found and represents the WIMP region of parameter space consistent with observation, with a certain confidence level.

The cross section region that can be explored shrinks at low WIMP masses, because of reduced sensitivity owed to the energy threshold of the detector. In other words WIMP with low mass produce a smaller energy deposition, which can be below detection threshold and thus it cannot be detected. Reducing the energy threshold of the detector, the cross-section
upper limit curve lowers and moves on the left thanks to an increased sensitivity to lighter WIMP masses (blue line).

The minimum of the exclusion curve is determined by the kinematic of the scattering process, which depends on the target nucleus. At larger WIMP masses the upper limit curve raises because of the suppression factor \(1/m_\chi\) (see Eq. (2.20))\(^3\).

In order to explore lower cross-section regions one has to increase the exposure, defined as the product of the target mass and exposure time (green line). Since the background scales up with the target mass, improved techniques are needed to enhance the signal/noise ratio.

The red line shows the exclusion curve when lighter target nuclei are used. Due to the kinematics of the elastic scattering and the reduction of \(v_{min}\) (see (2.21)) the minimum is shifted to the lower masses. In addition the overall sensitivity is reduced owed to a decreasing of spin-independent elastic scattering cross-section with lower A (see (2.15) and (2.16)).

\(^3\)Since the local dark matter density is constant, the heavier the WIMP mass, the lower is their number, thus less particles are available for the scattering process.
2.3 Dark matter directional experiments

In the landscape of WIMP direct detection experiments an increasing important role is held by directional experiments aiming at reconstructing both the energy and the track direction of a WIMP-induced nuclear recoil. The idea of directional detection was proposed by D. N. Spergel who observed that the WIMP motion with respect to the Earth would produce an anisotropy in the angular distribution, and therefore in the direction of nuclear recoils [82]. This implies a dependence of the differential rate for WIMP scattering on the angle that the recoil track forms with respect to direction of solar motion (see relation (2.29)), which is expected to be peaked in the direction of the Sun motion. This is generally referred to as dipole feature [84]. On the contrary, there are no reasons why neutron background sources produce a nuclear recoil spectrum with such anisotropy.

The interest in the directional detection is two-fold: (i) due to the directional signature of galactic dark matter it provides an unambiguous proof of the origin of the dark matter and (ii) it is the unique way to overcome the so called “neutrino-floor”, that remains an unexplorable region of the parameter space for the direction-insensitive experiment.

In order to detect DM with directional approach, until now many efforts have been pursued exploiting low-pressure gas detectors. This is due to the fact that very short track recoils (sub-µm range) are expected in a solid target, while recoil tracks that have millimeter extent are expected for gas target. This relaxes the requirements about the spatial resolution but has the disadvantage of a low detector mass per unit volume. Thus the hardest challenge for the directional experiment with gas detector is the scalability [85].

On the contrary, a solid target detector overcomes the scalability problems, the challenge being a spatial resolution and a target granularity that let to detect track lengths $\leq 100$ nm.

Thanks to the use of nuclear emulsion with very small crystals and an innovative optical scanning system, NEWSdm will be the first experiment to search for DM with a directional approach using a solid target.

2.4 NEWSdm experiment

The NEWSdm experiment is the first dark matter direct detection experiment that aims at measuring the direction of the WIMP-induced nuclear recoil by means of a solid target detector [86]. The core of the detector are a new generation of nuclear emulsions with nanometric AgBr crystals, called NIT (Nano Imaging Tracker) and U-NIT (Ultra-Nano Imaging Tracker). For the success of the experiment a very fast and high resolution readout system is necessary in order to scan the emulsion and reconstruct the nanometric recoil tracks. In this section the new generation emulsion will be illustrated together with an explanation of the experimental strategy of the NEWSdm experiment and the readout strategy.
2.4.1 Nuclear emulsions

Nuclear emulsions consist of small crystals of silver halide (AgX) with linear dimensions typically between 0.1 and 1 µm suspended in a gelatin medium composed of organic materials. After having had a leading role in particle physics for more than half of XX century, nuclear emulsion had a new start thanks to the development of automatized scanning systems capable of scanning and analysing large emulsion surface ([87, 88, 89, 90, 91, 92, 93]).

It is worth mentioning the success of the OPERA experiment, which thanks to huge number of nuclear emulsion used, was the first experiment to discover the $\nu_\mu \rightarrow \nu_\tau$ oscillations in appearance mode [94]. The nuclear emulsions used in the OPERA detector were made of AgBr grains of $\sim 200$ nm diameter.

When light or ionizing radiation passes through the emulsions, excitons are created, which then rapidly dissociate forming electron-hole pairs. An electron is captured by a trapping site on the grain surface producing a sensitization center (electronic process), which combines with an interstitial silver ion to form an Ag atom (ionic process). When the repetition of electronic and ionic processes occurs on the same site, an Ag cluster grows in dimensions [95]. An Ag atom on an AgX grain is unstable and dissociates to form a free electron and an interstitial silver ion within a few seconds. Instead, Ag$_2$ is stable, but it cannot initiate the development process. An Ag cluster becomes a so-called latent image center, capable to initiate the development process, when it is composed of four Ag atoms. Ag and Ag$_2$ formed on an AgX nanoparticle are therefore called a latent pre-image center and a latent sub-image center, respectively (see Figure 2.4 for the formation of latent image center).

![Figure 2.4: Steps for latent image formation. The latent pre-image center is unstable and unable to initiate a development process, a latent sub-image center is stable but unable to initiate a development process; a latent image center is stable and developable.](image-url)
The development process allows to discriminate between grains with or without a latent image center on their surface. During this process the latent image contained in an emulsion is made visible by the reduction of silver ions in the silver halide crystal to metallic silver. AgX grains without a latent image center are not modified during the development process and are than dissolved by a fixing solution.

A schematic picture of the track formation in a nuclear emulsion is shown in Figure 2.5.

![Figure 2.5: A schematic picture of the track formation in a nuclear emulsion](image)

NIT: Nano Imaging Trackers

Having a linear size of $\sim 200$ nm, OPERA-like emulsions are not suitable to detect WIMP-induced nuclear recoils, whose track length is expected to be of the order of few hundred nanometers. Nuclear emulsion made up of grains of $\sim 40$ nm diameter, instead, are not sensitive to minimum ionizing particles but are suitable to detect WIMP-induced nuclear recoils, thanks to the overwhelming number of electron-hole pair created in 40 nm AgX grain by the nuclear recoil [96].

An R&D project started in 2007 at the Nagoya University in collaboration with Fuji Co. experts led to the production of a new generation emulsion films with grain diameter $\sim 45$ nm and a linear density of crystals of about 11 crystals/µm: the so-called Nano Imaging Tracker (NIT) [97]. A further R&D led to the Ultra-Nano Imaging Tracker (U-NIT) whose grains have a diameter of about 20 nm and a linear density of 29 crystals/µm [98]. Figure 2.6 shows the dimensions of the crystal diameter for NIT and U-NIT emulsions measured with an electron microscope. The measurements refer to three different batches.

The NIT production is performed in three steps:

- mixing in a thermostatic bath of $\text{AgNO}_3$ and $\text{NaBr}$ to obtain the AgBr crystals, exploiting the reaction $\text{AgNO}_3 + \text{NaBr} \rightarrow \text{AgBr} + \text{Na}^+ + \text{NO}_3^-$. Polyvinyl alcol (PVA) is then added to ensure the uniformity of the grain size and NaI is also used in order to increase the quantum efficiency in the activation of the crystals;
Figure 2.6: Distribution of the crystal diameter measured with an electron microscope for NIT (left) and U-NIT (right) emulsions.

- mixing of AgBr crystals with gelatin while the residual extra ions ($\text{Na}^+$, $\text{NO}_3^-$) are extracted by means of a reduction process. The mixture is then centrifuged to have a uniform crystal distribution;

- mixing of the emulsion gel obtained with ultra-pure water and poured on a rigid support (usually glass or plastic).

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Mass Fraction</th>
<th>Element</th>
<th>Mass Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>AgBr-I</td>
<td>0.78</td>
<td>Ag</td>
<td>0.44</td>
</tr>
<tr>
<td>Gelatin</td>
<td>0.17</td>
<td>Br</td>
<td>0.32</td>
</tr>
<tr>
<td>PVA</td>
<td>0.05</td>
<td>I</td>
<td>0.019</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C</td>
<td>0.101</td>
</tr>
<tr>
<td></td>
<td></td>
<td>O</td>
<td>0.074</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N</td>
<td>0.027</td>
</tr>
<tr>
<td></td>
<td></td>
<td>H</td>
<td>0.016</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S</td>
<td>0.003</td>
</tr>
</tbody>
</table>

Table 2.2: Constituents of NIT emulsion (a) and chemical composition of NIT emulsion (b).

The density of the emulsion is 3.43 g/cm³. The mass fraction of NIT constituents and chemical composition of the NIT emulsion are reported respectively in tables 2.2(a) and 2.2(b).
2.4.2 Experimental strategy

NEWSdm uses a very innovative approach for the directional detection of WIMPs: the detector is based on the recent development of the NIT emulsion allowing to reach an extremely high spatial resolution. This makes it possible to achieve DM experiment with a solid target that does not suffer of limitations in mass scaling as gas-based detectors does.

The detector is conceived as a bulk of nuclear emulsions acting both as a target and tracking device. Since WIMP-induced recoils are expected to be peaked in the direction of Cygnus constellation, the detector will be placed on an equatorial telescope in order to cancel out the daily motion of the Earth and keep the orientation towards the Cygnus fixed.

The emulsion films will be placed in such a way that their surface will be parallel to the average direction of the WIMP wind. The track reconstruction will be performed in the $xy$ Galactic plane, being the $x$ axis opposite to the Cygnus constellation (see Figure 2.7).

The power of this technique is shown in Figure 2.8, where the expected 2D angular distribution of WIMP-induced nuclear recoils for a WIMP mass of 40 GeV/c$^2$ is depicted. The signal PDF is a Gaussian distribution (blue curve) while the background PDF is a uniform distribution (dashed red line) since it is assumed to be isotropic. The distribution are truncated at $\pi/2$ and $-\pi/2$ since it was conservatively assumed no sense-discrimination. Studies on the sense-discrimination with emulsion are ongoing and promising.

The width $\sigma_\theta$ of the Gaussian angular distribution is the convolution of two components:

$$
\sigma_\theta = \sqrt{(\sigma_{W_n-scatter}^\theta)^2 + (\sigma_{straggl}^\theta)^2}
$$

$\sigma_{W_n-scatter}^\theta$ represent the angular deviation of the nuclear recoils from the direction of the Earth’s motion, as it arises from the WIMP-nucleus scattering, while $\sigma_{straggl}^\theta$ is the angular deviation owed to the straggling in the emulsion target. The last term represents...
Chapter 2. WIMP Direct Detection and NEWSdm Experiment

Figure 2.8: 2D angular distribution of 100 WIMP-induced recoils and 100 background events. Signal and background components are represented as solid blue and dashed red lines, respectively. Recoils are produced for an emulsion target, a 40 GeV/c² mass WIMP and a 100 nm threshold.

the standard deviation of the distribution of the difference between the mean direction of a given track in the emulsions with respect to the initial direction of the recoil. For more details see the reference [99].

The presence in the emulsion gel of lighter nuclei in addition to silver and bromine, allows the NEWSdm detector to have a good sensitivity to WIMPs with both light and heavy masses. Indeed the sensitivity strongly depends on the minimum detectable track length. In turn the length of the recoiled track depends on the mass of the target nucleus and on the mass of incident WIMP, which settles the recoiling kinetic energy of the scattered nucleus. As far as the cross section is concerned, WIMPs prefer heavy targets (see (2.16)), but light WIMPs (O 10 GeV/c²) would produce nuclear recoils with small kinetic energy and thus having ranges too short to be detected, if scatter off an heavy target. Instead for light WIMPs kinematics favors light nuclei as target for a double effect: the WIMP energy transfer to nuclei with similar mass is maximal, and for the same energy lighter nuclei travel for a longer path length in emulsion than heavier one.

Figure 2.9 shows the track length of the recoiled nucleus for different target nuclei, as a function of its recoiling kinetic energy.

After the exposure the emulsion films will be developed and analyzed by means of fully automated microscopes. The red-out will be performed in two phases: a fast pre-selection of candidate signal tracks followed by a scanning with an ultra-high resolution system of the selected candidates. The goal is to achieve a resolution for the reconstruction of the track between 10 and 20 nm in position and better than 15° in angle.
2.4.3 Read-out system

To fulfill the requirements of an ultra-high resolution and a fast and a fully automated scanning system, a two step approach is required: a fast scanning with a state-of-the-art resolution for the signal pre-selection followed by a pin-point check of pre-selected candidates with unprecedented nanometric resolution to further enhance the signal to noise ratio and perform very accurate measurements of the range and the recoil direction.

The first step consists of the so-called shape analysis. This phase is performed by means of an improved version of the European Scanning System (ESS [88, 89]) and Super-Ultra Track Selector (S-UTS [90]), used for the scanning of the OPERA films. Thanks to an R&D program carried out by INFN groups a prototype with a resolution better than one order of magnitude with respect to the ESS and with a speed of 200 cm$^2$/h was set up[100] while a new system is being developed in Japan aiming at increasing the scanning speed up to 5000 cm$^2$/h. The shape analysis aims at distinguishing clusters of several grains from clusters made of a single grain produced by the thermal excitation (the so called fog) by means of the analysis of their shape. In fact, given the intrinsic resolution of the optical microscope ($\approx$ 200 nm), the sequence of several grains making a track of a few hundred nanometers long, appears as a single cluster. Therefore, to distinguish signal tracks from fog, one takes advantage of the fact that the cluster made of several grains tends to have an elliptical shape with the major axis along the direction of the signal track, while a cluster produced by a single grain tends to have a spherical shape.

In order to evaluate the efficiency of the optical system to observe submicrometric tracks a test beam with low velocity ions was performed. Kr ion beams with energy of 200 and 400 keV and C ion beams with energy of 60, 80 and 100 keV were used. Such beams are used to produce in emulsion tracks with lengths in the 100-300 nm range. Figure 2.10 shows how
Figure 2.10: Kr ions implanted in NIT films. The image is taken with an optical microscope. The selection of candidate tracks is based on the elliptic fit of the clusters.

Submicrometric tracks appear when analyzed by the optical microscope. Although single silver grains of the tracks are not resolved and appear as a single cluster, their elongated form is clearly visible [101]. Thus by means of an elliptical fit of the cluster shape it is possible to clearly separate fog grains by signal tracks. The threshold on the length of major axis is typically 1.25 or higher.

In order to evaluate the intrinsic angular resolution of the optical scanning system an analysis on emulsion films exposed to a 2.8 MeV neutron beam was performed. Having the hydrogen an higher neutron scattering cross section with respect to the other element of the emulsion gel, neutron-induced proton recoil tracks with length up to a few hundred of micrometers were produced. The analysis was performed as follows. A sample of tracks with lengths of tens of micrometers, made by a sequence of several elliptical clusters were selected. For these tracks the effect of the scattering within a few degrees are therefore negligible. Than the ellipticity cut on the clusters was applied. An evaluation of the angular difference ($\Delta \theta$) between the direction of the major axis of the elliptic cluster and the direction of the fitted track was carried out (see Figure 2.11(a)). As is shown in Figure 2.11(b) the distribution of $\Delta \theta$ results to be of Gaussian shape with a $\sigma \simeq 230$ mrad. This value obtained with the optical scanning system represents the intrinsic angular resolution, by far the best resolution achieved with direction sensitive detectors in this energy range.

In order to validate the shape analysis, selected tracks were than examined with an X-ray microscope. The X-ray microscope has an higher resolution ($\sim 60$ nm) but a too small scanning speed with respect to the optical microscope. In fact the analysis of a few hundred of $\mu$m$^2$ takes about 100 s. The X-ray analysis was used only to demonstrate the principle of selection by elliptical shape analysis and measure the efficiency achievable with the optical microscopy. In Figure 2.12 a comparison between the optical and X-ray images of candidate tracks is shown: thanks to the high resolution of the X-ray system grains belonging to the
same clusters can be resolved. In this way it is possible discriminate signal tracks from the background.

After a set of multi-grain tracks was selected, the shape analysis with the optical scanning system was applied on them, with a cut on the ellipticity of 1.25. The efficiency as a function of the track length is reported in Figure 2.13. 100% efficiency is reached when track lengths exceed 180-200 nm.

Being the scanning speed an issue in the analysis of a large mass detector, the X-ray microscopy is not feasible for the second step of the read-out strategy. Thus the aim was to enhance the optical microscopy improving in the spatial resolution.

The idea is to exploit the plasmon resonance effect occurring when nanometric metal grains are dispersed in a dielectric medium [102]. The polarization dependence of the resonance frequencies strongly reflects the shape anisotropy and can be used to infer the presence
of non-spherical nanometric silver grains. Figure 2.14 shows the results of the resonant light scattering from individual Ag nanoparticles [102]: spherical particles do not show any different response as a function of the incident polarization, while an ellipsoid is sensitive to the polarization.

The goal is to use this technique to retrieve track information in NIT emulsions beyond the optical resolution. This is obtained taking images of the same cluster with different polarization angles and looking at the position of its barycenter. In this way, a displacement of the position of the cluster barycenter can be observed. Making this analysis it will be possible to discriminate clusters made of single grains from those made of two or more grains. In particular if the observed displacement exceeds the position accuracy of a single grain, it would be the evidence for a multi-grain cluster produced by a signal track. Using a sample of nanosphere the position accuracy was measured. The unprecedented accuracy of 6 nm was achieved in both coordinate as shown in Figure 2.15.

2.4.4 Expected background

In order to unambiguously identify WIMP induced recoils, it is needed to reach ultra-low background experimental conditions.

As seen before, NIT emulsions are insensitive to MIP particles so the background sources for NEWSdm experiment are in principle $\alpha$ and $\beta$ particles, $\gamma$-rays and neutron induced recoils. The background can be divided in two categories: environmental and intrinsic. The former can be significantly reduced by a suitable shield, whose construction will be discussed in the next chapter being the subject of this thesis. The latter instead is an irreducible source of radiation thus is crucial to characterize and minimize, by using highly purified materials
Figure 2.14: Scattered-light spectra from individual Ag particles with spherical (left) and spheroidal (right) shape [102]. Arrows indicate the polarization of the incident light. A dependence of the response on the light polarization is observed for particles with ellipsoidal shape.

Figure 2.15: Position accuracy better than 10 nm with the plasmon resonant light scattering.

for the construction of the detector and of the shield, as well as for the structure of the apparatus.

The $\alpha$ radiation does not represent a problem. In fact the main $\alpha$-particles sources are Radon, U and Th radioactive chain. These sources produce $\alpha$-particles of MeV energy, thus having a range in emulsion of the order of tens of microns. Being their track lengths longer
than those produced by WIMP induced recoils, α-particles can be identified and discarded in the emulsion by an upper cut on the track length.

β rays represent a relevant source of background since they are produced in $^{14}$C decays present in the emulsion gelatin currently used. With a proper chemical treatment it is possible to regulate the emulsion response, in terms of number of sensitized crystals per unit path length (i.e. sensitivity), in such a way to make NIT insensitive to the electrons. A recent study carried out in Japan has shown that the emulsion sensitivity to electrons is strongly reduced at low temperatures [103]. Since γ rays produce electrons when interact with matter essentially by means of the photoelectric effect, Compton scattering and pair production, this cryogenic approach would present the big advantage to make negligible also the gamma-induced background. In view of very large exposures, the Collaboration is also exploring the possibility to cancel out the electron background from intrinsic $^{14}$C content, by replacing organic gelatine with synthetic polymers. Studies are ongoing.

Therefore the main background source is represented by neutron induced recoils. This is a dangerous background because it produces signal identical to WIMP-induced recoils, except for the angular distribution. There are four types of neutron sources:

- cosmogenic neutrons: neutrons produced by the muons in the surrounding rock, whose energy are as large as several GeV;
- external radiogenic neutrons: neutrons produced by the environmental radioactivity external to the experimental apparatus, mainly in $(\alpha,n)$ and spontaneous fission reactions, whose energy is of the order of the MeV;
- neutrons produced by muon interacting in the shield and detector materials;
- intrinsic radiogenic neutrons: produced in the detector due to its intrinsic radioactive contaminants.

The firsts two sources can be reduced to a reasonable level with an appropriate shielding that minimize the neutron production in the shield materials by muons. The fourth one would be responsible for an irreducible neutron yield. Starting from the U and Th activities of the emulsion and measured with Inductively Coupled Plasma Mass Spectrometry and with γ-spectrometry, the neutron yield has been estimated by means of a dedicated MC simulation based on the SOURCES code [104] at a value of $(1.2 \pm 0.4)$ n/(yr kg). The neutron energy spectrum, as calculated with SOURCES, was then used as the input for a GEANT4-based simulation in order to estimate the fraction of neutrons interacting in emulsion and laying in the signal region (that with a track length of the recoiled nuclei between $100 \text{ nm} \leq L \leq 1000 \text{ nm}$). The detectable neutron-induced background would be $0.06 \text{ yr}^{-1}\text{kg}^{-1}$ [105].

2.4.5 Experiment time scale

The NEWSdm collaboration plans to perform the first exposure with a target mass of 10 kg and the corresponding analysis of the data on a time scale of five years. The first year of
the project will be devoted to the realization of a pilot exposure of 10 g in order to confirm the estimations of the overall background budget of the experiment. The second and third year of the project, 2020-2021, will be devoted to the construction of the infrastructures, the production of the emulsion target and the detector shield. The exposure of 10 kg detector is foreseen by the beginning of 2022 and will last one year. The first results are foreseen by the end of 2023.
Chapter 3

Shield simulation

Neutrons can produce nuclear recoils via elastic scattering with target nuclei and generate a signal which is indistinguishable from that of WIMPs. Thus it is crucial for the success of the experiment to minimize the neutron-induced background. This chapter is dedicated to the simulation of the shield against external background. The aim is to design a shield for a pilot experiment with an exposure of 10 kg per year. This pilot experiment will act as a demonstrator to further extend the mass range. The Collaboration is committed to provide a Technical Design Report (TDR) for the pilot experiment in spring 2019. The results presented in this thesis work will be used as input for the TDR.

The simulation study was focused on the most dangerous background sources coming from cosmic radiation: cosmogenic neutrons and muons interacting in the shield and detector materials.

At first neutron interactions with matter will be described; then muon and cosmogenic neutron fluxes will be characterized; finally the results of the shield simulation will be reported.

3.1 Neutrons interactions with matter

Neutrons interact with matter via strong nuclear force. Being the strong nuclear force a short-range interaction and since the matter is mainly empty, neutrons result to be very penetrating particles. Neutrons can be classified according to their kinetic energy as shown in table 3.1.

<table>
<thead>
<tr>
<th>Energy</th>
<th>Energy classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal</td>
<td>&lt; 0.025 eV</td>
</tr>
<tr>
<td>Epithermal</td>
<td>0.025 - 1 eV</td>
</tr>
<tr>
<td>Slow</td>
<td>1 eV - 1 MeV</td>
</tr>
<tr>
<td>Fast</td>
<td>1 - 20 MeV</td>
</tr>
<tr>
<td>Ultrafast</td>
<td>&gt; 20 MeV</td>
</tr>
</tbody>
</table>

Table 3.1: Neutrons classification based on the kinetic energy.
The main processes that neutrons undergo in the shield and detector materials are:

- neutron capture \((n, \gamma)\);
- elastic scattering;
- inelastic scattering.

The dependence of the cross section of these processes with respect to the neutron kinetic energy for some elements used for the shield is shown in Figures 3.1, 3.2, 3.3, 3.4 [106]. Note that for the \(^{10}\text{B}\) the \((n, x)\) direct reactions play an important role.

![Figure 3.1: Neutron cross-section as a function of the neutron kinetic energy for an hydrogen target, for the elastic scattering (dotted line) and the neutron capture (dashed-dotted line). Elastic scattering is the dominant process in the whole energy range.](image)

When a neutron is absorbed by a nucleus to form a compound nucleus several reactions can occur. The neutron radiative capture \((n, \gamma)\), is the only possible absorption reaction for non-fissionable nuclei. The radiative capture results in the loss of the incident neutron associated with the emission of one or more \(\gamma\)-rays emitted by the excited compound nucleus decaying to the ground state. This process can occur at all incident neutron energies, but the cross section is much larger when the incident neutrons are thermal, and decreases as the neutron kinetic energy increases.

Elastic scattering may take place in two ways: (i) via compound nucleus formation followed by the emission of a neutron that returns the original nucleus to the ground state conserving the kinetic energy of the initial system; (ii) without neutron absorption and the formation of a compound nucleus as in classical billiard ball-like scattering.
Figure 3.2: Dependence of the neutron cross section on neutron kinetic energy for a $^{10}$B. Note the high value of the total cross section (2 order larger than hydrogen one at thermal energies), dominated at low energies by $(n, \alpha)$ reaction.

Figure 3.3: Neutron cross-section as a function of the neutron kinetic energy for $^{63}$Cu, for the elastic scattering (dotted line), inelastic (dashed line) and neutron capture (dash-dotted line). Inelastic scattering occurs for energies above $6 \cdot 10^5$ eV.

Following the approach of reference [107] we consider a neutron with a velocity $\mathbf{V}_1$ in the laboratory system that scatters off a nucleus with mass number $A$ at rest. In the center of mass system the neutron velocity is $\mathbf{v}_1 = \frac{A}{A+1} \mathbf{V}_1$ while the velocity of the target is
Inelastic scattering occurs for energies above $7 \cdot 10^5$ eV.

$v_2 = -\frac{1}{A+1} V_1$ (see Figure 3.5). After the elastic collision the velocities in the center-of-mass system are unchanged in magnitude. However, in the laboratory system the neutron velocity $V'_1$ is the vector difference of $v'_1$ and the center-of-mass velocity of the target $[-1/(A+1)]V_1$.

The law of cosines gives:

$$V'_1^2 = \left(\frac{A}{A+1} V_1\right)^2 + \left(\frac{1}{A+1} V_1\right)^2 - 2 \frac{V_1^2}{(A+1)^2} A \left(\frac{1}{A+1}\right)^2 \cos(\pi - \theta)$$

being $\theta$ the scattering angle in the center of mass system. From Eq. (3.1) it is straightforward to obtain the ratio of the neutron energy after the collision ($E$) and before the collision ($E_0$):

$$\frac{E}{E_0} = \frac{V'_1^2}{V_1^2} = \frac{1}{(A+1)^2} (A^2 + 2A \cos \theta + 1)$$

yielding to the important inequality:

$$\alpha \leq \frac{E}{E_0} \leq 1$$

where $\alpha = [(A - 1)/(A + 1)]^2$. To find the relation between $\theta$ and $\theta_L$, the laboratory scattering angle, using again the law of cosines for the triangle formed by $v_2$, $V'_1$, and the parallel to $v'_1$, and reminding that $|v'_1| = |v_1|$: 
Figure 3.5: (a) Collision between particles of equal mass. Left: center of mass system; right: laboratory system (velocities and momentum). (b) Collision between particles of mass 1 and 2. Left: velocity diagram; right: momentum diagram; the capital letter represent the quantity in the laboratory system while the small letters in the center of mass system. Unprimed quantities are before the collision; primed quantities are after the collision.

\[ V_1^2 = \left( \frac{A}{A+1} \right)^2 = V_{1'}^2 + \frac{1}{(A+1)^2} V_{1''}^2 - \frac{2V_1 V_{1'}}{A+1} \cos \theta_L \]

which, combined with Eq. (3.2), gives:

\[ \cos \theta_L = \frac{A \cos \theta + 1}{(A^2 + 2A \cos \theta + 1)^{1/2}} \quad (3.4) \]

For neutrons with energies up to at least a few hundred keV, the scattering is due only to the “s” wave and hence it is spherically symmetric in the center-of-mass system. The probability \( dW \) that the scattering occurs within a solid angle \( d\omega \) is thus proportional to \( d\omega \), that is:

\[ dW = \frac{d\omega}{4\pi} = \frac{\sin \theta d\theta}{2} = -\frac{d(\cos \theta)}{2} \quad (3.5) \]
Hence, after collision, the probabilities to have equal intervals of $\cos \theta$ are independently from $\theta$, i.e. the elastic scattering is isotropic in the center of mass system. By differentiating Eq. (3.2) one obtains:

$$\frac{dE}{E_0} = \frac{2A}{(A + 1)^2} d(\cos \theta) \quad (3.6)$$

i.e. equal intervals of $\cos \theta$ correspond to equal intervals of energy. From Eq. (3.6) we conclude that the probability that after one collision the neutron has an energy between $\alpha E_0$ and $E_0$ is uniform (see Figure 3.6). Note that for $A = 1$, i.e. the hydrogen nucleus, $\alpha = 0$ so the neutron can in principle loose all the energy in only one elastic scattering event. Actually, it is clear that the probability of a single value in a continuum distribution is zero. Note also that in the case of hydrogen the average energy after $n$ collisions, is $\langle E_n \rangle = (1/2^n)E_0$.

![Figure 3.6: Neutron energy $E$ after one collision in case of isotropic scattering in the center of mass system for a neutron of initial energy $E_0$ where $\alpha = [(A - 1)/(A + 1)]^2$.](image)

In treating the slowing down of neutrons\(^1\) it is convenient to use the so called lethargy defined as $u = \ln(E_0/E)$ where $E_0$ is an arbitrary reference energy and $E$ is the neutron energy. A useful quantity is the main value of the lethargy $\langle u \rangle = \xi$ called also the “logarithmic energy decrement per collision”:

$$\xi = \langle \ln \frac{E_0}{E_1} \rangle = \frac{\int_{A\alpha E_0}^{E_0} \ln \frac{E_0}{E_1} \frac{dW_1}{dE_1} dE_1}{\int_{A\alpha E_0}^{E_0} \frac{dW_1}{dE_1} dE_1}$$

\[= \frac{(A + 1)^2}{4AE_0} \int_{\alpha E_0}^{E_0} \frac{E_0}{E_1} dE_1 = 1 + \frac{(A - 1)^2}{2A} \ln \frac{A - 1}{A + 1}\] \quad (3.7)

where $dW_1/dE_1$ represents the not-normalized probability density function for a neutron to have energy equal to $E_1$ starting from a reference energy $E_0$. Note that $\xi$ is function of $A$ only and it does not depend on the neutron energy. Table 3.2 shows the value of $\xi$ for different $A$.

\(^1\)Often one refers to the slowing down of the neutrons as moderation.
Thus each collision decreases the average value of $\ln E$ by $\xi$, and hence, after $n$ collisions we have:

$$\langle \ln E_n \rangle = \ln E_0 - n\xi$$ (3.8)

From Eq. (3.8) it is possible to evaluate the number of collisions needed to slow down neutrons of a given energy. For example if $E_0 = 1\text{MeV}$ the number of collisions required to reach the thermal energy ($0.025\text{eV}$) is 17.5 for hydrogen and 111 for carbon (see Table 3.3).

<table>
<thead>
<tr>
<th>A</th>
<th>1 (H)</th>
<th>2 (D)</th>
<th>12 (C)</th>
<th>16 (O)</th>
<th>56 (Fe)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\xi$</td>
<td>1</td>
<td>0.725</td>
<td>0.158</td>
<td>0.120</td>
<td>0.035</td>
</tr>
</tbody>
</table>

Table 3.2: Logarithmic energy decrement per collision for various elements.

Table 3.3: Collision required to thermalize 1 MeV neutrons for various elements, through elastic scattering.

**Inelastic scattering** occurs when the nucleus is left in an excited state by the collision of the nucleus. Thus after the collision a radiation is emitted causing the nucleus to fall in the ground state. Since it is a threshold process, the energy required for inelastic scattering to occur is $[108]$:

$$E = \frac{m_N + M}{M} \epsilon$$ (3.9)

where $m_N$ is the mass of the neutron, $M$ that of the target nucleus and $\epsilon$ is the energy level of the nucleus excited state.

Also the so called “direct reactions” are inelastic processes if the target nucleus is left in an excited state. They are scattering processes which involve a projectile which is enough energetic to have a reduced wavelength ($\lambda/(2\pi)$) of the order of 1 fm that interacts with single valence nucleon. Examples of this reaction are $(n, n)$, $(n, p)$, $(n, 2n)$, $(n, \alpha)$ producing a compound nucleus by absorbing the scattering neutron, and emitting a neutron, a proton, two neutrons or an $\alpha$ particle, respectively.

### 3.2 Cosmic ray muons

The characterization of cosmic rays is essential for all experiments aiming at searching for rare events as WIMPs, since they are responsible for one of the most dangerous background component: muon-induced neutrons background.

Cosmic rays arriving on the Earth at an average rate of $\sim 1000\text{ particles/m}^{-2}\text{s}^{-1}$ are mostly ionized nuclei but also an electronic component is present. As concern ionized nuclei
they are essentially protons (90%) $\alpha$ particles (9%) and heavier nuclei. They present an energy spectrum (see Figure 3.7) that follows a power law of the form:

$$\frac{dN(E)}{dE} \propto E^{-(\gamma+1)} \quad (3.10)$$

up to energy of $10^{20} \text{ eV}$. The spectral index $\gamma + 1$ assumes different values in different regions of the spectrum. Up to the so called “knee” it is $\approx 2.7$; between the knee and the “ankle” the spectrum steepens to $\gamma + 1 \approx 3.0$; finally it returns to $\gamma + 1 \approx 2.7$ for energies above the ankle [110].

![Figure 3.7: Measured Cosmic ray spectrum [109].](image)

Primary cosmic rays produce secondary particles via inelastic interactions with particles of the atmosphere, among them there are charged pions and kaons. From the decay chain of the charged mesons are produced muons, mainly in the high atmosphere, typically 15 km above the sea level. The energy and angular spectrum at sea level result from the convolution of the production spectrum, the energy loss in the atmosphere, and the decay.

The overall angular distribution at the ground shows a $\cos^2 \theta$ behaviour, being $\theta$ the zenith angle, which is typical of muons with $E_\mu \sim 3 \text{ GeV}$. At lower energies the angular distribution
becomes steeper, while at higher energy it flattens, approaching a \( \sec \theta \) distribution for \( E_\mu \gg \epsilon_\pi \) and \( \theta < 70^\circ \), being \( \epsilon_\pi = 115 \text{ GeV} \) the critical energy for pions [111]. This is the characteristic energy below which the decay probability of the pion in the atmosphere is larger than the interaction probability. For kaons the critical energy is \( \epsilon_K = 850 \text{ GeV} \).

As far as more energetic muons are concerned, an approximate formula for the muon double-differential rate at sea level assuming a negligible muon decay rate \( (E_\mu > 100 \text{ GeV}/\cos \theta) \) and neglecting the curvature of the Earth, \( (\theta < 70^\circ) \) is [111]:

\[
\frac{dN_\mu}{dE_\mu d\Omega_\mu} \approx \frac{0.14 E_\mu^{-2.7}}{\text{cm}^2 \text{ s sr GeV}} \times \left\{ \frac{1}{1 + \frac{1.1 E_\mu \cos \theta}{115 \text{ GeV}}} + \frac{0.054}{1 + \frac{1.1 E_\mu \cos \theta}{850 \text{ GeV}}} \right\}
\]

(3.11)

where the two terms give the contribution of pions and charged kaons. This expression, together with the above defined energy conditions imply that at large angles the flux is smaller but more energetic than at low angles.

### 3.2.1 Cosmic ray muons in underground laboratories

Muons are very penetrating particles and reach to significant depths underground. A depth-intensity-relation can be found in literature [112] for laboratory depths in the range (1-10) km water equivalent (w.e.):

\[
I(h) = I_1 e^{-h/\lambda_1} + I_2 e^{-h/\lambda_2}
\]

(3.12)

where \( I(h) \) is the muon intensity corresponding to the slant depth \( h \). Using experimental data from different underground laboratories, estimates of the parameters \( I_1, I_2, \lambda_1, \lambda_2 \), can be obtained (see reference [112]). The accuracy of Eq. (3.12) results to be about 5%.

In the case of a laboratory with flat overburden it is simple to evaluate the total muon intensity at a vertical depth \( h_0 \) under the surface. Neglecting the curvature of the Earth, the muon intensity for a slant depth \( h \) at a zenith angle \( \theta \) is:

\[
I(h, \theta) = I(h) G(h, \theta)
\]

(3.13)

where \( G(h, \theta) = \sec \theta, h = h_0 \sec \theta \) and \( I(h) \) is the muon intensity expressed in Eq. (3.12). Thus the previous equation can be written as:

\[
I(h, \theta) = (I_1 e^{-h_0 \sec \theta/\lambda_1} + I_2 e^{-h_0 \sec \theta/\lambda_2}) \sec \theta
\]

(3.14)

The total muon intensity is given by an integration over the upper hemisphere. Thanks to experimental data for the total muon flux from underground laboratory at a given vertical depth (see references in [112]) it is possible to define a fit function of the muon intensity versus the vertical depth \( h_0 \):

\[
I_\mu(h_0) = 67.97 \cdot 10^{-6} e^{-h_0/0.285} + 2.071 \cdot 10^{-6} e^{-h_0/0.698}
\]

(3.15)

where \( h_0 \) is expressed in km w.e. and \( I_\mu(h_0) \) is in units of \( \text{cm}^{-2}\text{s}^{-1} \).
For laboratories under a mountain the additional information about the mountain shape is necessary to determine the correct total muon flux:

\[ I_{\text{tot}} = \int \sin \theta d\theta \int d\phi I(h(\theta, \phi))G(h, \theta) \] (3.16)

where the information regarding the mountain shape is contained in \( h(\theta, \phi) \). An “equivalent vertical depth” for the laboratories located under a mountain can be calculated by estimating the total muon intensity with Eq. (3.16), using it as input for Eq. (3.15) and solving it with respect \( h_0 \).

![Figure 3.8: Total muon flux for various underground laboratories. For the sites located under a mountain the equivalent vertical depth has been determined. The curve is the result of the fit carried out with equation (3.15) to data taken from site with flat overburden [112].](image)

For LNGS an equivalent vertical depth of \((3.1 \pm 0.2) \text{ km w.e.}\) was estimated, using the information about the mountain shape and the differential muon intensity provided by the MACRO collaboration [113]. Figure 3.8 shows the total muon flux at different underground laboratories.

### 3.3 Muon-induced neutrons at LNGS

Muon-induced neutrons have a spectrum extending up to GeV energies, thus are more difficult to suppress with respect to those from environmental radioactivity. As seen in the previous section, LNGS have an equivalent vertical depth equal to \((3.1 \pm 0.2) \text{ km w.e.}\). This depth corresponds to a mean muon energy of about 250 - 300 GeV (see Figure 3.9).

There are three dominant processes of neutron production by muons underground:
muon inelastic scattering on nuclei via electromagnetic interactions, producing a nuclear disintegration and therefore neutrons. In particular, in deep inelastic scattering muons emit a virtual photon that interact with the nucleus causing the disintegration. This process is also called “direct muon spallation” [115];

- neutron production by hadrons in muon-induced hadron cascades. In this case neutrons are generated by spallation reactions of cascade-hadrons (\(\pi^\pm, K^\pm, n, p\)) on nuclei [114];

- production in muon-generated electromagnetic cascades, where neutrons are produced by \(\gamma\) in shower undergoing photonuclear interactions.

The muon-induced neutron production rate depends strongly on the chemical composition and the density of the material crossed by muons. Thus the knowledge of the rock and concrete composition in an underground laboratory is essential for the simulation of the neutrons generated by muons. These simulations were carried out in the reference [112] for different underground sites, and the total muon-induced neutron flux was estimated. These values are reported in Figure 3.10 as a function of the depth, together with the fit function of the following form:

\[
\phi_n = P_0 \frac{P_1}{h_0} e^{-h_0/P_1}
\]

where \(\phi_n\) is the total muon-induced neutron flux, \(h_0\) the equivalent vertical depth, and the fit parameters are \(P_0 = (4.0 \pm 1.1) \times 10^{-7} \text{cm}^{-2}\text{s}^{-1}\) and \(P_1 = (0.86 \pm 0.05) \text{ km w.e.}\).

Figure 3.11 shows the neutron energy spectrum for the different underground site.
The relative angular distribution of the produced neutrons with respect to the muon track were also obtained. It is evident a peak in the direction of the muon track, as expected for the neutrons produced via muon spallation [116], while secondary evaporation neutrons show an isotropic distribution with respect to muon tracks.

3.4 Shield simulation for 10 kg detector

The simulation of the shield for a detector of 10 kg of NIT was performed in the present thesis work. For this purpose the GEANT4 software [117] was used. GEANT4 offers different alternatives for the Physics List, that is the class that collects particles and physical processes used by the software for the simulations. The Physics List used for the simulation of the shield is QGSP-BERT-HP [118]. It simulates the hadronic interactions of nucleons, pions and kaons using Bertini model for intranuclear cascade [119] up to 10 GeV, while the quark gluon string model [120] is used for higher energy reactions. It contains standard electromagnetic processes. As far as muons are concerned, muon capture and muon-nuclear reaction such as spallation and photo-nuclear interactions induced by muons are included. High precision data driven models for low energy neutrons transport and interaction are also implemented.

3.4.1 Guidelines for shield construction

First of all it is essential to distinguish the fast neutrons induced by muons in two classes: (i) those produced by muons in the last meters of the external rock and concrete of the laboratory and (ii) those produced by muons in the shield and in the detector itself. The latter can be discarded through an effective external veto surrounding the detector if the time information is collected. The former, instead, cannot be put in coincidence with

![Figure 3.10: Total muon-induced neutron flux at different underground site [112]](image-url)
primary muons, and can be suppressed only through an effective passive shield.

As the NEWSdm detector integrates the signal during the whole exposure time without having time information, neutrons induced by muons in the shield constitute a very dangerous background source and have to be accurately evaluated, after that the shield against neutrons coming from the rock has been defined. Thus for the shield simulation a two step approach was followed: (i) find the best configurations to have the required shielding power against neutrons from the external rock; (ii) evaluate the shielding power against muon-induced neutrons in the shielding and detector.
From section 3.1 it is clear that in order to stop neutrons an hydrogenous material has to be used. In fact hydrogen has a quite high capture cross section for thermal neutron and an high neutron elastic scattering cross section. Moreover, having almost the same mass of the neutron it is able to stop it in only one elastic collision (see Eq. (3.3)). Furthermore it results to have a high logarithmic energy decrement per collision ($\xi$) and a low number of collisions is necessary to thermalize energetic neutrons (see Table 3.3).

Since neutrons have energies up to the GeV (see Figure 3.11) the elastic scattering becomes less effective in slowing down neutrons. The risk is that these neutrons are slowed down at energies in range of the WIMP ones but are not absorbed. Thus, in order to avoid too large shield thickness, other processes, in particular inelastic scattering in high Z and high A materials, result to be effective in reducing significantly the neutron energy. Thus for neutrons in the GeV energy range the best shielding configuration consists of a layer of high Z material, followed by a low Z material with high hydrogen content such as polyethylene. This scheme takes advantage of high inelastic cross sections, that include also the above-mentioned direct reactions in high Z materials to reduce effectively the neutron energy. Lower energy neutrons generated in this process are then better attenuated by moderation, down to thermal energy, and absorbed in hydrogenous material. The first high-Z layer is also efficient in shielding $\gamma$ radiation. Such a configuration allows to reduce the overall shielding dimension with respect to a solution with only hydrogenous material, requiring larger thickness to attenuate ultrafast neutrons [122].

As a drawback, in high Z materials muons have a larger probability to interact and to produce very high energy neutrons, that can arrive at the detector with attenuated energy and mimic the WIMP signal.

For simulations with two material configuration of the shield (in the following we refer to 1MCONF and 2MCONF configurations of the shield with one and two material layers, respectively), copper is chosen as heavy material. This is due to its high purity and to the fact that it has muon-induced neutron production rate that is 2.5-3 times smaller than lead [112].

In the present work a spherical shielding is used.

### 3.4.2 Simulation setup

The simulated NIT emulsion layer is a parallelepiped 50 $\mu$m-thick with a frontal size of $30 \times 36$cm$^2$. The NIT layer is poured on a plastic base of polymethyl methacrylate (PMMA) 1 mm-thick. The emulsion film is made of a NIT layer and PMMA layer. With a NIT density of 3.43 g cm$^{-3}$ each layer results to have a mass of 18.52 g, so a stack of 540 film is needed to have 10 kg detector, for a total volume of $30 \times 36 \times 56.7$ cm$^3$. A spherical shielding was simulated around the target, with a 50 cm inner radius (see Figure 3.13).

### 3.4.3 Results

Below we report the results for the simulation with the cosmogenic neutrons, i.e. the neutrons produced by muon interactions in the rock, and for the simulation with the muons
emerging from the rock of the LNGS. A background track is defined as a nuclear recoils whose track length is in the range (100-1000) nm, where the lower limit stands for the minimum detectable track length with the current scanning system, while the upper limit is applied for background rejection. As an example, alpha particles produce longer tracks that can be discarded in this way. Proton recoils are not considered as background since NITs result to be insensitive to them. Nuclear recoils are considered as a signal if it is fully contained within the NIT emulsion. Thus if a nucleus comes from outside it is discarded.

**Cosmogenic neutrons**

Cosmogenic neutrons used as primary particles in Monte Carlo simulations were provided by XENON collaboration [121], which were obtained by propagating cosmic ray muons in the rock of Gran Sasso mountain. The angular and energy spectra of cosmogenic neutrons are shown in Figures 3.14 and 3.15.

In order to estimate the rate of background events for a total exposure of 10 kg·yr a total flux of $\phi_{c.n.} = 7.3 \times 10^{-10}\text{cm}^{-2}\text{s}^{-1}$ for cosmogenic neutrons at LNGS was considered [112].

Figures 3.16 and 3.17 report the background rate and the mass of the shield for a 1MCONF, as a function of the shield thickness. Water and polyethylene are considered as shielding materials, respectively.

As expected the rate of background events decreases as the thickness of hydrogenous material increase, except for statistical fluctuations (that are evident in the case of 4 m and 4.5 m of water). Both water and polyethylene shields show a level of background rate lower than 1 event/(10kg·yr) for shield thickness between 60 and 80 cm.

Figure 3.18 shows the rate of background events for the 2MCONF where the inner material is polyethylene followed by a copper layer. On the x-axis the thickness of the copper layer is reported, while the colored dots stay for different polyethylene thicknesses. Thus the total thickness of the shield is given by the sum of the two values.
As expected these results show an enhancement of the shielding power with respect to 1MCONF. For example the shield configuration with 40 cm of polyethylene and 15 cm of copper shows the same shielding power as for 100 cm polyethylene. This allows to have more compact solutions for the shield, but this shielding power against cosmogenic neutrons could be canceled out by the larger interaction rate of muons in the high Z material of the shield.

Muons

In order to simulate the muons surrounding an Hall of LNGS the MUSUN (MUon Simulations UNderground) generator software created by V. A. Kudryavtsev was used [123]. The generated muon was then used as input for HepMC\(^2\) event record generator and interfaced

\(^2\)The HepMC package is an object oriented event record written in C++ for High Energy Physics Monte Carlo Generators. It can be used as both a “container class” for storing events after generation and also as a “framework” in which events can be built up inside a set of generators.
CHAPTER 3. SHIELD SIMULATION

Figure 3.16: Water shield. (a) Rate of background events for a 10 kg detector and exposure time of one year as a function of shield thickness; (b) shield mass versus shield thickness.

Figure 3.17: Polyethylene shield. (a) Rate of background events for a 10 kg detector and exposure time of one year as a function of shield thickness; (b) shield mass versus shield thickness.

with GEANT4 for the simulations of the shield behaviour. The angular and energy spectra of generated muons are shown in Figures 3.19 and 3.20.

The total expected muon flux at LNGS is $\phi_\mu = (1.159 \pm 0.03) \text{m}^{-2}\text{s}^{-1}$ [124].

After preliminary simulations where the behavior of several shield configurations have been tested for muons, four configurations have been selected for repeated simulations in order to reduce statistical errors. As expected, the configurations with large copper thickness show high rate of background tracks, thus all have been discarded except the one with 80 cm of polyethylene and 15 cm of copper. In the table 3.4 we report the background event rate for neutron and muon simulations, as well as the total rate for the four selected shield
Figure 3.18: Shield configuration with two materials: polyethylene inside, copper outside. (a) Rate of background events for a 10 kg detector and exposure time of one year as a function of copper thickness for different polyethylene layers; (b) shield mass versus copper thickness for different polyethylene layers. The total thickness is given by the sum of the copper thickness (value of the abscissa) and polyethylene one (indicated in the legend).

Thus the best shield configuration is the one with 100 cm of polyethylene showing the lowest total background rate. As expected the last configuration of the table 3.4 that shows the smallest background rate induced by cosmogenic neutrons is poisoned by muon interactions...
Figure 3.19: Cosmic ray muon angular distributions at LNGS obtained with MUSUN software. Left: azimuth angle distribution; right: zenith angle distribution.

Figure 3.20: Cosmic ray muon energy spectrum at LNGS.

in the copper layer of the shield.

Further improvements

The background rate induced by muons can be considerably reduced by means of topological cuts on an event by event basis. In fact the event that mimics a WIMP signal is the neutron elastic scattering, where nothing is produced except the recoiling nucleus track. When different tracks are produced in the same event, the event can be rejected, thus reducing the background. Four categories of events with this topology have been identified:

- nucleus is produced by neutron or proton inelastic scattering, in which a proton or more than one photon are also produced;
- nucleus is produced by the coulomb scattering or inelastic interaction of a muon, in which a muon is present at the vertex where the nuclear recoil is generated;
Table 3.4: Rate of background tracks estimated for different configurations of the shield, produced by cosmogenic neutrons and muons. Also the total rate is reported in the last column.

<table>
<thead>
<tr>
<th>Shield config.</th>
<th>neut. sim. rate events/(10kg*yr)</th>
<th>mu sim. rate events/(10kg*yr)</th>
<th>total rate events/(10kg*yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>80 cm polyethylene</td>
<td>0.68 ± 0.07</td>
<td>0.42 ± 0.04</td>
<td>1.1 ± 0.08</td>
</tr>
<tr>
<td>100 cm polyethylene</td>
<td>0.51 ± 0.06</td>
<td>0.46 ± 0.04</td>
<td>0.97 ± 0.07</td>
</tr>
<tr>
<td>90 cm poly + 5 cm copp.</td>
<td>0.55 ± 0.06</td>
<td>0.61 ± 0.03</td>
<td>1.16 ± 0.07</td>
</tr>
<tr>
<td>80 cm poly + 15 cm copp.</td>
<td>0.39 ± 0.05</td>
<td>0.88 ± 0.04</td>
<td>1.27 ± 0.06</td>
</tr>
</tbody>
</table>

Figure 3.21: Rate of background events for different shield configurations.

- inelastic scattering of pion, where the hadron in the point where nucleus is created;
- nucleus is produced in the so-called “Bertini model” for intra-nuclear cascade, in which the recoiling nucleus is produced with energetic photons and one or more hadronic particle (mainly protons).

These kind of events could be discarded if NIT emulsions are alternated with OPERA-like films in a sandwich structure. OPERA films are, indeed, sensitive to MIP and low \(dE/dx\) allowing to detect also tracks that are invisible to the NIT.

Thus if we consider as background events only nucleus tracks produced by neutron elastic scattering, the background rate of events, is considerably reduced as shown in table 3.5 and Figure 3.22.

The best shielding power is still given by the configuration with 100 cm of polyethylene where thanks to the topological study the background rate is reduced to (0.75 ± 0.06)/(10kg*yr).
CHAPTER 3. SHIELD SIMULATION

<table>
<thead>
<tr>
<th>Shield config.</th>
<th>neut. sim. rate</th>
<th>mu sim. rate</th>
<th>total rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>80 cm polyethylene</td>
<td>0.68 ± 0.07</td>
<td>0.23 ± 0.023</td>
<td>0.91 ± 0.07</td>
</tr>
<tr>
<td>100 cm polyethylene</td>
<td>0.51 ± 0.06</td>
<td>0.24 ± 0.024</td>
<td>0.75 ± 0.06</td>
</tr>
<tr>
<td>90 cm poly + 5 cm copp.</td>
<td>0.55 ± 0.06</td>
<td>0.33 ± 0.026</td>
<td>0.88 ± 0.07</td>
</tr>
<tr>
<td>80 cm poly + 15 cm copp.</td>
<td>0.39 ± 0.05</td>
<td>0.51 ± 0.04</td>
<td>0.90 ± 0.06</td>
</tr>
</tbody>
</table>

Table 3.5: Rate of background tracks estimated for different configurations of the shield, produced by cosmogenic neutrons and muons. For the latter only recoiling tracks produced by neutron elastic scattering are considered. Also the total rate is reported in the last column.

Figure 3.22: Rate of background events for different shield configurations. For simulations with muons only recoiling nuclei produced in neutron elastic scattering are considered.
Chapter 4

NEWsdm optical microscope

The development of an automatic scanning system was the key element for the success of the nuclear emulsion as detector in many modern particle experiments. Even if conceived for the first time in 1974 at Nagoya University [125] the first fully automated scanning system for nuclear emulsion was realized in 1990 and was named the Track Selector (TS) [126]. While upgraded versions of the TS had been developed and used in different experiments such as DONuT and CHORUS [127, 128], an automatic microscopy R&D program started in Italy, aimed at developing an automated scanning system for the analysis of large emulsion surfaces for the OPERA neutrino oscillation experiment. Those efforts led to the development of the European Scanning System (ESS) [89, 129] that together to the Super-Ultra Track Selector (S-UTS) [90] were largely used in the OPERA experiment. With a resolution of 1 micron in position and 3 mrad in angle, these systems analyzed OPERA emulsion films with a scanning speed of 20 cm$^2$/h for ESS and 72 cm$^2$/h for S-UTS.

A dedicated R&D program on automatic scanning system is conducted by Naples OPERA group since 2011, leading to the development of the Large Angle Scanning System for OPERA framework (LASSO) [91] that allowed to improve the performance of ESS achieving a scanning speed of 24 cm$^2$/h in Stop&Go mode (SG) and 40 cm$^2$/h in Continuous Motion mode (CM), without hardware setup modifications. The R&D was extended to the design of a new hardware for the microscope that has led to the record scanning speed of 190 cm$^2$/h.

The progress achieved in both nuclear emulsion production and scanning readout system allowed to extend the application of nuclear emulsion to different fields such as muon radiography, dark matter search and medicine.

This chapter describes the ESS and its upgrades. I then describe the development of a super-resolution optical microscope using so-called “Local Surface Plasmon Resonance” (LSPR) phenomenon. Finally, I describe the upgrade of the illumination system of the optical microscope, performed in May 2018.
4.1 ESS

The scanning of nuclear emulsion is performed by taking a series of tomographic images of the emulsion layer, while the focal plane of the objective lens is moving through its thickness, thus digitizing the full content of the sample. Then the image processing and the three dimensional reconstruction are carried out, allowing to obtain the key information of developed grains: position, shape and brightness. The high data flow coming from fast digital cameras requires high performance hardware and efficient image processing and computing algorithms.

The European Scanning System took its inspiring ideas from the “SySal” (SYstem of SALerno) [130], an automatic scanning system developed by the University of Salerno to take part in the scanning phase of nuclear emulsions of CHORUS experiment.

The main components of the ESS are (see Figure 4.1):

- A computer controlled motorized scanning stage for horizontal (XY) motion;
- A computer controlled motorized stage mounted vertically (Z) for focusing;
- A granite arm carrying the Z stage and the optical system;
- Optics;
- Digital camera for image grabbing mounted on the top of the optical tube, with a vision processor;
- An illumination system placed below the optical bench.

All the components are hosted on a rigid and vibration-free optical bench. The latter and the vertical stage were developed in collaboration with ‘MICOS company customizing commercial products for specific requirements. They are equipped with the stepping motors “Vexta NanoStep RFK Series 5-Phase Microstepping System” produced by Oriental Motor company. The motors are driven by a National Instrument controller “PCI-7344” inserted into the host pc. The motion parameters, that is maximum speed, acceleration and deceleration, are set in such a way to minimize the time needed to move from one field of view to the adjacent one. During the data taking the vertical stage moves at constant speed equal to $v_z = sf$ where $f$ is the camera frame rate and $s$ is the length of sampling step. With a frame rate of 400 frames/s and sampling distance of 3 $\mu$m the resulting speed is 1150 $\mu$m/s. Thus the time needed to scan a 44 $\mu$m thick emulsion (the thickness of OPERA-like emulsion), is $\sim$ 55 ms, including the time for acceleration, deceleration and the time needed to load parameters motion by the host. Adding the time needed to move to the adjacent field of view (horizontal displacement) one gets the time to complete the whole working cycle that results to be $\sim$ 170 ms.

Figure 4.2 shows a schematic representation of the ESS optical system. The alignment (within 1 mrad) of stages, illumination system and lenses is a basic request in order to achieve stringent resolutions (2 mrad for OPERA experiment).
CHAPTER 4. NEWSDM OPTICAL MICROSCOPE

Figure 4.1: The European Scanning System microscope.

The optical system is infinity corrected and include a tube lens located in a trinocular tube and the objective lens. The latter is the Nikon CFI Plan Achromat 50× oil-immersion, N.A = 0.9, W.D. = 0.4. The choice was dictated by requests on the working distance, given by the overall thickness of the emulsion layers and the plastic base ((44 + 205 + 44) µm), and numerical aperture that define the ultimate image resolution (sub-micron resolution requires N.A. > 0.8).

The illumination system is placed below the scanning table and was designed to operate under the conditions of Köhler illumination. The source is a tungsten halogen lamp with a computer controlled power supply. The illuminating light is focused on the aperture diaphragm of a condenser (lens) by a collector (lens). The achromatic (Nikon, N.A.=0.8, W.D.=4.6 mm) condenser illuminates the emulsion layers with a parallel beam. A green filter and a frosted glass are inserted after the collector in order to obtain a uniform and monochromatic illumination.

The Mikrotron MC1310 high-speed megapixel CMOS camera is configured to take 376 frames per second (fps). The camera sensor resolution is 1280 × 1024 pixels, with the pixel size equal to 12 × 12 µm². Images are finally grabbed and processed by means of a Matrox Odyssey XPro frame grabber/vision processor.

This hardware is coupled with a software system that for each cycle has the tasks of: (i) move the optical system; (ii) acquire images via frame grabber; (iii) process images and store them in a buffer and (iv) perform cluster and track recognition. This system has achieved the scanning speed of 20 cm²/h.
4.1.1 ESS upgrade: the new generation scanning system

According to the way the microscope stage and objective move, two different approaches can be distinguished for the scanning method: Stop&Go (SG) and Continuous Motion (CM) (see Figure 4.3). Different scanning speed can be reached with these two methods.

As we have already said, just by implementing LASSO software modules, developed by Naples OPERA group, on the ESS hardware configuration, it was possible to enhance the scanning speed to 24 cm$^2$/h in SG and 40 cm$^2$/h in CM.

The SG technique includes two steps: the data acquisition (DAQ) motion and the reset motion. During the DAQ motion acquisition, since the objective lens moves vertically at a constant speed $v_z = sf$, in order to increase the objective lens speed the fastest camera frame rate and the largest sampling distance have to be chosen. The latter is, however, limited by the focal depth of the objective lens and a compromise solution has to be found. In fact, on one hand objective lens with larger focal depth allows to use bigger sampling step, but on the other hand it produces images with shadows from more distant grains, thus increasing the processing load and decreasing the purity by elevating the combinatorial background level.

The reset motion involves the objective (along Z) and stage (in XY) motion to the next field of view. When the time needed by the reset motion is determined by the horizontal movement, e.g. when emulsion thickness is smaller than field of view, the total time required to carry out a working cycle can be written as:

$$T_{SG} = \frac{d}{v_z} + 2 \frac{v_z}{a_z} + 2 \sqrt{\frac{h_x}{a_x}} + T_{oh}$$  \hspace{1cm} (4.1)
where \( d \) is the emulsion thickness, \( a_x \) and \( a_z \) are accelerations along X and Z respectively, \( h_x \) is the horizontal distance between adjacent fields of view and \( T_{oh} \) is the overhead time. The latter is a constant time required by the software to carry out a series of operations required by the implementation. The first two terms of Eq. (4.1) represent the time required by the DAQ motion. It consists of an acceleration step to the speed \( v_z \) with constant acceleration \( a_z \), a movement with constant speed \( v_z \) along the thickness \( d \) and a deceleration step until complete stop that takes the same time of the first step. The third term of Eq. (4.1) represents the time required to cover the distance \( h_x/2 \) with constant acceleration \( a_x \), that is the reset motion.

The scanning speed is also influenced by the dimension of the field of view of the optical system. In fact a wider field of view reduces the number of working cycles needed to cover a given area. The way for enlarging the field of view without loss in image quality is to use an objective lens with lower magnifications combined to a camera with smaller sensor pixel dimension and a higher number of pixels. This is necessary not to worsen the pixel to micron ratio, often called the optical pixel size.

Thus the key points that the upgrade of the ESS had to pursue in order to increase the scanning speed was:

- Reduce the DAQ motion time by means of a camera with faster frame rate combined with a larger focal depth objective lens;

- Reduce the number of views to scan by using a lower magnification objective lens in combination with a camera with smaller sensor pixels and a higher number of pixels.

With this in mind a new hardware selection was made in order to upgrade the ESS and enhance its performances, designing and constructing the new generation scanning system (NGSS) \[92\]. The modular structures of the LASSO system provide the flexibility needed to upgrade the system following the technological progress.
The new hardware components used in the NGSS device are:

- Mikrotron MC-4082 camera. The MC-4082 is a monochrome CMOS digital camera with a resolution of $2336 \times 1728$ pixel (or 4M) and operates at 563 fps. It has almost the same sensor size as MC-1310, even if with smaller sensor pixel equal to $7 \times 7 \, \mu m$, hence it can be used directly without optics modification. With 8 bits/pixel the output data rate will be 2.1 GB/s;

- Nikon Plan Fluor 20×/0.75NA objective lens. This objective lens combined with the new camera allows to keep the pixel size at the same level as it was in the ESS (0.3 $\mu m$/pixel), which in turn will allow using the same algorithms and parameters for image processing;

- Matrox Radiant eV-CXP frame grabber. The Matrox Radiant eV-CXP is equipped with the CoaXPress (CXP), a new camera interface standard, that takes advantage of common coax cabling to transmit images at rates and distances beyond previous standards. With CXP, image data can be transmitted at up to 800 MB/s using a single coaxial cable and up to 3.125 GB/s using four cables to a maximum of 40 meters. By means of the PCIe 2.0 x8 host interface Matrox Radiant eV-CXP can be handle data rate up to 4 GB/s. Also Silicon Software microEnable 5 frame grabber was tested and similar results were obtained;

- Graphics Processing Unit (GPU) boards (GeForce GTX-690 or better). A GPU board is required to replace the Odyssey Xpro image processing power. Image processing is ideal for implementing on GPU and thanks to the Compute Unified Device Architecture (CUDA), GPUs can be used for general purpose processing.

In table 4.1 are compared the specification of new components of the NGSS with those of the ESS.

The LASSO scanning parameters and performances for both the ESS and upgrade system are listed in table 4.2. The big improvement in scanning speed is clear. The effective speed of $84 \, \text{cm}^2/\text{h}$ takes into account the 30 $\mu m$ overlap along X and Y axis between two adjacent views and the overhead time.

The CM approach, depicted schematically at the bottom of Figure 4.3 establishes that the vertical axis moves with periodic motion while the stage moves horizontally at a constant speed, in such a way that during one period of the objective lens oscillation, its displacement is equal to one field of view. If necessary, the overlap of two adjacent field of view can be increased by decreasing the horizontal speed of the stage.

The CM mode has the big advantage of reducing the time needed for the reset motion and eliminating the overhead time [93].

In the CM mode with LASSO software framework, the record scanning speed of 190 cm$^2$/s was achieved [93].
<table>
<thead>
<tr>
<th></th>
<th>ESS</th>
<th>NGSS</th>
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</thead>
<tbody>
<tr>
<td><strong>Objective lens</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manufacturer</td>
<td>Nikon</td>
<td>Nikon</td>
</tr>
<tr>
<td>Type</td>
<td>Plan Achromat</td>
<td>Plan Fluor</td>
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<tr>
<td>Magnification</td>
<td>50×</td>
<td>20×</td>
</tr>
<tr>
<td>Numerical Aperture</td>
<td>0.90</td>
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</tr>
<tr>
<td>Working Distance</td>
<td>0.35 mm</td>
<td>0.35 mm</td>
</tr>
<tr>
<td>Eff. Depth of Field</td>
<td>6 μm</td>
<td>4 μm</td>
</tr>
<tr>
<td>Optical filter</td>
<td>No</td>
<td>Green</td>
</tr>
<tr>
<td><strong>Camera</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manufacturer</td>
<td>Mikrotron</td>
<td>Mikrotron</td>
</tr>
<tr>
<td>Model</td>
<td>MC-1310</td>
<td>MC-4082</td>
</tr>
<tr>
<td>Image sensor</td>
<td>CMOS</td>
<td>CMOS</td>
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<tr>
<td>Sensor Pixel</td>
<td>$12 \times 12 \mu m^2$</td>
<td>$7 \times 7 \mu m^2$</td>
</tr>
<tr>
<td>Resolution</td>
<td>$1280 \times 1024$ (1.25Mpix)</td>
<td>$2336 \times 1728$ (4Mpix)</td>
</tr>
<tr>
<td>Frame rate</td>
<td>376 fps</td>
<td>563 fps</td>
</tr>
<tr>
<td>Data rate</td>
<td>470 MB/s</td>
<td>2100 MB/s</td>
</tr>
<tr>
<td><strong>Frame Grabber</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manufacturer</td>
<td>Matrox</td>
<td>Matrox/SiliconSoftware</td>
</tr>
<tr>
<td>Model</td>
<td>Odyssey XPro</td>
<td>eV-CXP/microEnable 5</td>
</tr>
<tr>
<td>Camera interface</td>
<td>SFCL (up to 680 MB/s)</td>
<td>CXP (up to 3.125 GB/s)</td>
</tr>
<tr>
<td>Host interface</td>
<td>PCI-X (up to 1 GB/s)</td>
<td>PCIe 8x (up to 4 GB/s)</td>
</tr>
<tr>
<td><strong>Image Processor</strong></td>
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<td></td>
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<tr>
<td>Manufacturer</td>
<td>Matrox</td>
<td>nVidia</td>
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<tr>
<td>Model</td>
<td>Odyssey XPro</td>
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<td>Chipset</td>
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<td>SW library</td>
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<td>CUDA</td>
</tr>
</tbody>
</table>

Table 4.1: LASSO scanning parameters and performances for both ESS and upgrade system.

### 4.2 Super-resolution optical microscope

In order to obtain the sensitivity, competitive with other DM search experiments, the minimal detectable track length of a recoiling nucleus in emulsion should not exceed 100 nm [131]. As described in the paragraph 2.4.3 the emulsion scanning is based on a two step approach in order to increase the scanning speed: at first a shape analysis is carried out with an optical microscope, to select track candidates; then track candidates are analyzed by means of an higher resolution device. The latter step could be performed by means of a complex device like an X-ray microscope but has two disadvantages: (i) the experiment would become more complicated since the data read out could not be carried out in the same site of the experiment, (ii) the analysis phase would be significantly slowed down.

Hence the idea to develop a super-resolution optical microscope, exploiting the local surface plasmon resonance (LSPR) generated when an incident light wave interacts with...
<table>
<thead>
<tr>
<th></th>
<th>ESS</th>
<th>NGSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frame rate (fps)</td>
<td>376</td>
<td>563</td>
</tr>
<tr>
<td>Field of view (µm × µm)</td>
<td>390 × 310</td>
<td>805 × 595</td>
</tr>
<tr>
<td>Pixel to micron ratio (µm/pixel)</td>
<td>0.31</td>
<td>0.34</td>
</tr>
<tr>
<td>Z sampling step (µm)</td>
<td>2.66</td>
<td>1.75</td>
</tr>
<tr>
<td>Frames per view</td>
<td>16</td>
<td>28</td>
</tr>
<tr>
<td>Scanning depth (µm)</td>
<td>42.5</td>
<td>49</td>
</tr>
<tr>
<td>Vertical stage speed (µm/s)</td>
<td>1000</td>
<td>985</td>
</tr>
<tr>
<td>DAQ time (ms)</td>
<td>50</td>
<td>57</td>
</tr>
<tr>
<td>Reset time (ms)</td>
<td>70</td>
<td>102</td>
</tr>
<tr>
<td>Overhead time (ms)</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Working cycle (ms)</td>
<td>150</td>
<td>189</td>
</tr>
<tr>
<td>Views overlap (µm)</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Scanning speed (cm²/h)</td>
<td>24</td>
<td>84</td>
</tr>
</tbody>
</table>

Table 4.2: LASSO scanning parameters and performances for both ESS and upgrade system.

Conductive nanoparticles like silver grains (see paragraph 2.4.3), dispersed in a dielectric medium, like the organic gelatine [132]. The R&D performed by Italian and Japanese groups led to the first realization of such a device, whose prototype was designed and constructed in Naples and it is shown in Figure 4.4.

The optical system is composed by a Nikon oil objective lens with high magnification (100×) and high numerical aperture (N.A. = 1.45) and a magnifying lens Nikon VM C (2.5×). A 4Mpixels camera with a field of view of 65 × 48 µm and a digital resolution of 27 nm/pixel is placed at the end of the optical tube. The illumination system, that reproduces Köhler illumination conditions, was modified with respect to the ESS one, passing from a bright-field illumination to epi-illumination system. The latter has the advantage that only the light interacting with the specimen arrives at the camera. This enhances the optical contrast. The illuminating light source is a 18 W UV (λ = 406) nm LED. The prototype was equipped with a manual rotatable polarizer in order to exploit the polarization dependence of the LSPR effects.

The optical resolution of the prototype was measured to be 207 nm. Angular resolution measured by elliptical fit of grains belonging to a long track was equal to 235 mrad (13°). The position accuracy measured exploiting LSPR effect was 10.5 nm [132]. Nowadays an accuracy better than 7 nm has been achieved.

### 4.2.1 Illumination system upgrade

In this thesis work the upgrade of the illumination system is described. Two goals were pursued: (i) increase the light output and contrast by passing from the Köhler-type illumination system to the critical-type (or Nelsonian-type) one; (ii) make the microscope capable of measuring the wavelength of the LSPR by passing from monochromatic to the white light illumination. The latter goal enables direct measurement of the silver grain size.
and, hence, allows measuring the head-tail sense of a nuclear recoil.

Proper illumination system is crucial in order to obtain high quality images in microscopy. One of the most commonly used microscope illumination scheme is the Kölher illumination. This scheme has the advantage to produce a uniformly bright specimen illumination.

The light paths in a Kölher illumination are shown in Figure 4.5. A collector lens collects the light from the source. After passing through the field diaphragm it is focused onto the plane of the aperture diaphragm placed in the back focal plane of the condenser lens. The latter lens projects a parallel light beam to the specimen. Since the light source is not focused on the specimen, the latter is hit by a grainless and extended illumination that does not suffer from dust and imperfections on the glass surface of the condenser or from a non uniformity of the light source.

This can be seen also from the conjugate planes of the illuminating light path and image-forming light path. The former includes light source plane, condenser aperture diaphragm, the back focal plane of the objective and the eyepoint of the eyepiece; the latter are the field diaphragm, the specimen plane, the intermediate image plane and the retina (or the sensor plane of a camera).

Note that the condenser aperture diaphragm determines the numerical aperture of the microscope system, thus its careful regulation is needed.

The super-resolution optical system is characterized by a very small field of view. Thus, reproducing the Kölher scheme, especially when used in the epi-illumination mode, has the disadvantage to reflects back also the light rays coming from the outside the field of view, as
Figure 4.5: Illuminating light path (left) and image-forming light path (right) in Kölher illumination.

illustrated in the Figure 4.6. As a consequence a deterioration of the optical contrast occurs.

Figure 4.6: Kölher illuminations conditions in epi-mode illumination scheme. The red arrows indicate rays that from the outside of the field of view enter the objective lens.

In order to overcome this problem a different illumination scheme was implemented: critical illumination. In this scheme the light coming from the source is focused on the specimen plane through the condenser lens (in bright-field illumination scheme). As consequence the source image is projected on the specimen and thus seen in the retina (or sensors of a cam-
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Figure 4.7: Critical illuminations conditions in epi-mode illumination scheme. Light is focused in the focal point of the objective lens, and nothing from outside of field of view is reflected back to the objective.

This can often lead to a grainy, uneven, or speckled background. For this reason the critical illumination scheme is used only with very uniform light source. On the other hand this scheme can be effectively used with the epi-illumination scheme. Moreover it does not suffer from the reflection problems like it happens with the Köhler scheme. In fact the parallel light beam arriving onto the objective lens is then focused in its focal point as shown in Figure 4.7.

Figure 4.8: Schematic representation of the realized critical illumination system. A LED light source (on the right of the figure) is placed in the back focal plane of a first lens from which a parallel beam emerges. Then the light is focused by a second lens in its back focal plane that coincides with the back focal plan of a third lens. This latter send a parallel light beam to the objective lens (the green line on the left). In correspondence with the back focal plane of the second and third lens a diaphragm is located (the thin blue line).

In order to realize it the system depicted in Figure 4.8 was constructed. The light coming from a LED source (extreme right of the figure) located in the back focal plane of a collector lens and emerging parallel from it, is then focused in the back focal plane of a second converging lens where a diaphragm is located. A third lens is placed in such a way that its back focal plane coincides with that of the second lens. The parallel light beam emerging from the third lens is thus transmitted to the objective lens (the green line on the extreme
left of the Figure 4.8) and focused on the specimen (see Figure 4.7).

In order to avoid chromatic aberrations caused by the use of the white light, doublet lenses have been employed, to correct chromatic aberrations. Moreover the monochromatic camera used for the NGSS system has been replaced with Mikrotron EoSens 4CXP MC-4087 (4M pixel). It has the same sensor as the monochrome camera but additionally equipped with a Bayer Pattern filter. Since the camera sensor is sensitive only to the intensity of the incoming light, a color reconstruction algorithm, the so-called demosaicing process, has been implemented in LASSO.

Figure 4.9: (Left) Bayer filter scheme. It results by the repetition of the elemental $2 \times 2$ photosite matrix with two green elements, one red and one blue. (Right) Resulting pattern when white light hits Bayer filter.

Figure 4.10: Interpolation method implemented in LASSO. The information of the two missing colors of a given pixel, is retrieved by a simple arithmetic mean from the neighbor pixels.

Figure 4.9 shows on the left the Bayer filter scheme. It is given by the repetition of the elemental $2 \times 2$ photosite matrix with two green elements, one red and one blue. In this way 50% of pixels result to be green, 25% blue and 25% red. On the right is shown the resulting pattern when the white light hits the camera sensor. Each photosite allows only the right wavelength light to pass. In this way image results to be composed by pixels with only one wavelength light for each one. To convert an image from the bayer format to an RGB per pixel format, it is needed to interpolate the two missing color values in each pixel.
Several interpolation methods exist. The one implemented in LASSO is shown in Figure 4.10. According to this method the information of the two missing colors of a given pixel, is retrieved by a simple arithmetic mean from the neighbor pixels. After the interpolation is carried out, LASSO has the information of RGB intensities for each pixel.

Figure 4.11: Optical elements transmission/reflection spectra are reproduced. Lenses 1-3 are the lenses used for the illumination system while lens-4 is that of the objective and BS for beam splitter. Green, red and blue stay for the spectra of the color filters of the single phtosites. The spectrum of the light source is given by the orange line.

Figure 4.12: Color channel spectra obtained by the convolution of the LED source and microscope optical elements spectra with which of the respective color filter. The intensity (area) of each spectrum is normalized to the green spectrum.

Since the LED source, Bayer filter and microscope elements optical spectra are not flat over the visible wavelength range, (see Figure 4.11), the obtained color intensity distribution,
being the convolution of those, may be different from that of the original image. To fix it
a color correction operation is performed by LASSO. After the calculation, the RGB color
spectra are normalized to that of the green color (see Figure 4.12). The inverse of the
obtained values are used as weight to retrieve the correct RGB intensities of the image.

The described procedure of color retrieving was tested on the surface of a damaged
mirror. The Figure 4.13 shows the image of the mirror scratch after the various steps have
been applied. Figure 4.13(a) shows the image as seen by a monochrome camera sensor.
Figure 4.13(b) shows Bayern pattern image where the intensity of only one wavelength for
each pixel is recorded. In Figure 4.13(c) the colored Bayer pattern image is depicted; thanks
to the knowledge of the position of the color filter for each photosite, each pixel acquires
the color of the corresponding superimposed filter. Figure 4.13(d) shows the mirror image
after LASSO has performed the two missing color interpolation for each pixel. Since the
green channel spectra have greater intensity with respect to the red and blue ones, the
image is green-dominated. Finally in Figure 4.13(e) the color-corrected image of the mirror
is reported.

![Figure 4.13: Testing of LASSO algorithm of color retrieving on the surface of a damaged
mirror. (a) Monochrome image; (b) Bayer pattern image; (c) colored Bayer pattern image;
(d) color interpolated image; (e) color-corrected image.](image)

The new hardware set-up was used to perform the first tests of multi-wavelength LSPR
analysis of silver nanorods with dimensions of $40 \times 80 \text{ nm}^2$ and $40 \times 120 \text{ nm}^2$. In Figure 4.14
the LSPR peaks are clearly visible. The different colors correspond to different wavelengths
at which plasmon resonance occurs. The latter depends on the orientation of the nanorod
with respect to the polarization direction of the light. In particular the peak resonance is expected to occur at red light wavelength when the light polarization is parallel to the long side of the $40 \times 120 \text{ nm}^2$ nanorods; at green wavelength when the light polarization is parallel to the long side of the $40 \times 80 \text{ nm}^2$ nanorods; at blue wavelength when the light polarization is perpendicular to the long side of both $40 \times 80 \text{ nm}^2$ and $40 \times 120 \text{ nm}^2$ nanorods.

Finally the multi-wavelength LSPR has been performed on a NIT emulsion exposed to $\alpha$ particles. Figure 4.15 shows the track of an $\alpha$ particle with red colored end-point grain. The red shift of the LSPR wavelength indicates the presence of a larger grain that is in accordance with major energy release at the end of the particle track before stopping due to the Bragg peak. This allows to measure the head-tail sense of nuclear recoil, thus, increasing the experiment sensitivity.

![Figure 4.14: LSPR analysis performed on silver 40 $\times$ 80 nm$^2$ (left) and 40 $\times$ 120 nm$^2$ (right) silver nanorods. Blue color corresponds to the direction of the longest axis of the nanorod perpendicular to the polarization direction.](image-url)
Figure 4.15: LSPR analysis performed on NIT emulsion hit by α particles. Note the red colored end-grain which indicate an elongated grain with respect blue and green. This is a clear indication of the particle sense.
Conclusions

The NEWSdm (Nuclear Emulsion for Wimp Search with directional measurements) experiment aims at detecting WIMP-induced nuclear recoils and measure their direction and energy. The detector is made by a new generation of nuclear emulsion films, the Nano Imaging Tracker (NIT) formed by silver-halide grains with dimension of 45 nm, allowing to detect sub-micron tracks. A super-resolution optical microscope has been developed to identify and reconstruct track candidates already selected by a first level analysis called “shape analysis”.

The latter aims to select track candidate by means of the analysis of the cluster shape. Indeed the cluster made of several grains tends to have an elliptical shape with the major axis along the direction of the signal track, while a cluster produced by a single grain due to the thermal excitation (fog) tends to have a spherical shape. After the shape analysis the track candidates will be analyzed by means of the super-optical resolution microscope. This microscope, exploiting the phenomenon of Local Surface Plasmon Resonance (LSPR), is capable of discriminating clusters of single grains from those made of two or more grains looking at the displacement of the point where LSPR happens, with a position accuracy better than 10 nm.

For the success of the experiment a negligible background is required, i.e. less than $\sim 1 \text{ event/(10 kg*yr)}$. Thus intrinsic background has to be controlled by using high-purity materials; moreover external background has to be to pull down through the use of a shield.

As the NEWSdm detector integrates the signal during the whole exposure time without having time information, the shield has to satisfy two conditions: (i) shield effectively neutrons coming from the rock and (ii) show an efficient behavior with neutrons produced by muons in the detector or in shielding materials. In fact without time information the latter cannot be excluded by means of a veto system.

Different configurations of the shield have been simulated: configuration with 1 material (1MCONF) where the chosen material was an hydrogenous one; configuration with 2 materials (2MCONF) where a material with high $Z$ is combined hydrogenous one and it is placed externally. The 2MCONF results to be very effective to shield very fast neutrons like cosmogenic ones (energies up to 3 GeV). The high $Z$ material has chosen to be the copper, for its high purity and the lower number of muon-induced neutrons when compared e.g. with lead, by a factor 2.5 to 3.

Although the 2MCONF has shown to shield very effectively cosmogenic neutrons also with small shield thickness, a thicker copper layer increases the total background due to interactions of muons in the copper layer. Thus the 1MCONF with 1 m of polyethylene
results to be the best with a total background of $(0.97 \pm 0.07)$ events/(10 kg*yr).

However further improvements of the background level can be reached by inserting OPERA-like emulsion between NIT in a sandwich structures. In fact, being the latter sensible also to minimum ionising particles, almost all type of events can be discarded except the pure neutrons-nucleus elastic scattering. This allows to achieve a background level of $(0.75 \pm 0.06)$ events/(10 kg*yr) with the previous configuration. Moreover also 2MCONF shows background levels below 1 events/(10 kg*yr).

Finally the new illumination system of the super-resolution optical microscope has allowed to perform the first multi-wavelength analysis by means of the local surface plasmon resonance (LSPR) called also plasmon analysis. This has shown very encouraging results on alpha tracks, having demonstrated to enable direct measurements of grain size, allowing to measure the head-tail sense of the nuclear recoils.

This feature enhances the NEWSdm sensitivity to the discovery of WIMPs.
Bibliography


