Neutron Backscattering Technique for the Detection of Buried Organic Objects

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Chapter 1

Introduction

In the field of explosives detection and demining, several techniques have been studied. Among many conventional techniques, nuclear techniques [1, 2, 3] have shown advantages, specially considering the new materials used in the fabrication of explosives which escape detection using conventional methods like metal sensors. One of the nuclear techniques that are being investigated in different countries is the Neutron Backscattering Technique (NBT) which is based in the fact that the buried target is Hydrogen-rich and therefore if it is in a media with different Hydrogen content and it is exposed to a fast neutron source, the number of backscattered thermal neutrons produced by the moderation process will give us a signal from which we can infer the presence of the Hydrogen-rich target.

Although nuclear techniques like NBT have been studied before [1, 3, 4], special problems need to be understood as well as is necessary to study the advantages, disadvantages and limits of the technique in the Colombian case. One of the most important issues that have to be investigated is the soil moisture. In order to detect the object the media in which it is buried has to be considered; the presence of water in the soil implies an extra amount of Hydrogen that will generate a background in the distribution of the backscattered neutrons. If the Hydrogen content of the soil is similar to that of the buried object, this will not be detected [5]. In this work NBT is studied experimentally and using Geant4 simulations to take into account the response of the technique to different geometrical parameters as well as the dependence with the moisture content in the soil.

In Chapter 2 the basic aspects of the neutron interaction with matter are presented together with a description of how the neutrons are detected. In Chapter 3 these basic aspects of the neutron interaction are simulated with the Geant4 toolkit. Chapter 4 begins with the description of the Neutron Backscattering Technique, showing how it is possible to detect buried Hydrogen-rich objects, followed by the results obtained with Geant4 simulations using as a test object a dummy mine (TNT simulant). In Chapter 4 the experimental set-up is described together with the obtained results including humidity. Chapter 5 shows the results obtained using the HYdrogen Density Anomaly Detector (HYDAD-D) [1] developed at the University of Cape Town, South Africa. The last Chapter describes the principal conclusions and expectations.
Chapter 2

Basic aspects of the neutron-matter interaction

The Neutron Backscattering Technique is based in the property of Hydrogen-rich materials to slow down efficiently a neutron beam. The interaction of neutrons with matter depends on its energy and of course on the properties of the target. In this chapter the main aspects of the neutron interaction with matter are described together with a short description of a neutron detector.

2.1 Introduction

Neutrons are classified according to their kinetic energy $E$ as:

- Fast: a few hundreds keV to a few MeV.
- Epithermal: between 100 keV and 0.1 eV
- Thermal: $E \approx kT$, at $T = 20 ^\circ C \rightarrow E \approx 0.025$ eV
- Cold: $\mu$eV to meV

The interaction of the incoming neutron with the nuclei of the target material may take place through:

- Elastic scattering from nuclei, which is the principal energy loss mechanism of fast neutrons.
- Inelastic scattering in which the target nucleus is left in an excited state which may latter decay by $\gamma$-rays or other radiative emission.
- Radiative neutron capture, important at thermal energies.
- Other nuclear reactions $(n,p)$, $(n,d)$, $(n,\alpha)$, etc.

The total cross section for a neutron interacting with matter will be given by the sum of the individual cross sections for each kind of reaction:

$$\sigma_{tot} = \sigma_{elastic} + \sigma_{inelastic} + \sigma_{capture} + ...$$ (2.1)
With this total cross section we can calculate the mean free path $\lambda$ for neutrons in matter as:

$$\lambda = \frac{A}{N_A \rho \sigma_{tot}},$$

(2.2)

where $\rho$ and $A$ are the mass density and the atomic weight of the target respectively and $N_A$ is Avogadro’s number.

Like photons, the intensity of a beam of neutrons is exponentially attenuated when passing through matter. The number of neutrons $N$, traversing a material with thickness $x$ without any interaction is:

$$N = N_0 \exp(-x/\lambda),$$

(2.3)

where $N_0$ is the number of incident neutrons. It is custom to call $\mu = 1/\lambda$ the attenuation coefficient and the ratio $N/N_0$ the survival probability, that is to say the probability that a neutron goes through the material without any interaction. This expression, however is only useful assuming mono-energetic and parallel neutron beams.

2.1.1 Elastic scattering

![Elastic scattering diagram]

Figure 2.1: Elastic scattering in the laboratory system and in the center of mass system. A neutron (mass $m$) with initial velocity $v_0$ (in the laboratory system) is scattered by a target nucleus (mass $M$) initially at rest ($V_i = 0$ in the lab system). The initial velocities of the projectile and the target in the center of mass system are $v_0'$ and $V_0'$, respectively.

The elastic scattering of neutrons by nuclei of the target material is the principal energy loss mechanism of fast neutrons. This reaction can be treated classically [7, 8]. Figure 2.1 shows the kinematics of the elastic scattering of a neutron (mass $m$) with initial velocity $v_0$ in the laboratory system, colliding with a target nucleus (mass $M$) initially at rest ($V_i = 0$ in the laboratory system). Taking as mass unit the neutron mass ($m = 1$, $M = A$), the neutron and the nucleus velocities...
in the CM system ($\vec{v}_0'$ and $\vec{V}_0'$ respectively) are related by:

$$\vec{v}_0' = \frac{A}{A + 1} \vec{v}_0$$  \hspace{1cm} (2.4)$$

$$\vec{V}_0' = -\frac{1}{A + 1} \vec{v}_0.$$ \hspace{1cm} (2.5)$$

The neutron velocity after the collision in the laboratory system is $\vec{v}_f = \vec{v}_0' + \vec{V}_0'$. Using the law of cosines we have:

$$(v_f)^2 = (v_0')^2 + (V_0')^2 + 2v_0'V_0' \cos(\theta_{cm}),$$ \hspace{1cm} (2.6)$$

where $\theta_{cm}$ is the scattering angle in the center of mass system (see Figure 2.1). Substituting eq. (2.4) and eq. (2.5) in eq. (2.6), the ratio of the neutron final and initial ($E$ and $E_0$) energy can be written as:

$$\frac{E}{E_0} = \left( \frac{(1/2)mv_f^2}{(1/2)mv_0^2} \right) = \frac{A^2 + 1 + 2A \cos(\theta_{cm})}{(A + 1)^2}. \hspace{1cm} (2.7)$$

The neutron energy after one elastic collision, depending on $\theta_{cm}$, will be in the interval:

$$\alpha E_0 \leq E \leq E_0,$$ \hspace{1cm} (2.8)$$

with $\alpha$ given by:

$$\alpha = \left( \frac{A - 1}{A + 1} \right)^2. \hspace{1cm} (2.9)$$

If $A = 1$ (the target nucleus is Hydrogen) then $\alpha = 0$ and the energy of the scattered neutron will fall in the interval:

$$0 \leq E \leq E_0. \hspace{1cm} (2.10)$$

This last result means that in a single collision the incoming neutron has certain probability of transferring almost all its energy, reaching low or thermal energies, if the target has low atomic mass. The process of reaching thermal energies by elastic collisions is known as thermalization or moderation.

To have an idea on how many collisions, in average, a neutron will need to reach low or thermal energies, the logarithmic change in energy is considered [7]:

$$u = \ln \frac{E_0}{E}, \hspace{1cm} (2.11)$$

which is known as "lethargy change". Taking into account eq. (2.7) we get:

$$u(\theta) = \ln \frac{(A + 1)^2}{A^2 + 1 + 2A \cos(\theta_{cm})}, \hspace{1cm} (2.12)$$
2.2 Neutron detection

Due to neutron charge absence its detection process is based in the production of charged particles by nuclear reactions. The strong dependence of the cross section of this reaction with the neutron energy has yield to the development of different kind of detectors depending on the neutron energy region \[6\]. In Figure 2.2 we see the total cross section for three different targets commonly used in thermal neutron detection. The reaction \[^3\text{He}(n,p)^3\text{H}\] has the highest cross section in the thermal region and is the one used in the NBT set-up in the present work as we will see in Chapter 4.
2.2 NEUTRON DETECTION

Figure 2.2: Total cross sections for three different targets commonly used in neutron detection ($^{3}$He, $^{6}$Li and $^{10}$B) as function of the neutron energy. The cross section for thermal neutrons ($E = 0.025$ eV) is about 4 orders of magnitude larger than the cross section for fast neutrons ($E = 1$ MeV).

2.2.1 The $^{3}$He proportional counter

In a $^{3}$He-based detector, the reaction that takes place inside the detector is:

$$n + ^{3}\text{H} \rightarrow p + ^{3}\text{H}, \quad Q = 0.764 \text{ MeV}. \quad (2.16)$$

A proton (p) and a triton ($^{3}$H) are produced in the reaction and then ionize the gas inside the detector. For thermal neutrons the cross section for this reaction is $\sigma = 5316$ b, while for fast neutrons ($E \approx 1$ MeV) it falls to $\sigma = 0.83$ b (see Figure 2.2). This gives a high efficiency for thermal neutron detection making the detector, at the same time fairly insensitive to fast neutrons. The thermal neutrons energy is small compared with the $Q$ value of the reaction, and therefore the products will share the available energy:

$$E_{p} + E_{^{3}\text{He}} = Q = 0.764 \text{ MeV}. \quad (2.17)$$

Momentum and energy conservation yields to

$$m_{^{3}\text{He}}v_{^{3}\text{He}} = m_{p}v_{p}, \quad (2.18)$$

$$\sqrt{m_{^{3}\text{He}}E_{^{3}\text{He}} = \sqrt{m_{p}E_{p}}. \quad (2.19)}$$

Solving eqs. (2.17) and (2.19) the products will be produced in opposite directions with energies:
CHAPTER 2. BASIC ASPECTS OF THE NEUTRON-MATTER INTERACTION

2.2.2 The wall effect

The charged particles produced in the nuclear reaction in the detector (p and ³H in the ³He-based detector) will deposit their energy, ionizing the ³He gas. If the products are completely stopped inside the detector it is expected a peak at 0.764 MeV in the measured spectrum (see Figure 2.3). If the reaction occurs near the walls of the detector it may happen that one of the products escape from it before depositing all its initial energy. This depends of course on the products range which depends on the characteristics of the detector as its pressure and density. If the range is comparable with the detector dimensions they have higher probability to escape from the detector leaving only part of its energy. This phenomenon is known as the wall effect, and it will yield to a spectrum with a quasi-gaussian peak at $E_p + E_{³H}$ with a long tail with a minimum energy at $E_{³H}$ (see Figure 2.3).

\[
\begin{align*}
E_p &= 0.573 \text{ MeV}, \\
E_{³H} &= 0.191 \text{ MeV}.
\end{align*}
\]
Chapter 3

Neutron Physics with Geant4

It is important to realize that simulation is a controlled experiment. In the simulation one has access to the involved parameters and one can decide to modify them. It has to be kept in mind that each model that the simulation includes have to be in agreement with what it is expected to happen in the considered energy region. For this purpose the whole problem has to be divided in several steps or phenomena and compare each one with known experimental or theoretical results. In this work the toolkit for simulation of the radiation-matter interaction Geant4 [9] is used. This toolkit has been used in fields such as high energy physics, medical physics and radioprotection. Although its results have been validated in a large number of works the source code has so many variables and options that for the purpose of the present work, it has to be checked that the chosen physics models are being implemented in the proper way. This chapter follows this purpose and it will give us confidence in the results of the final and complete simulation of the Neutron Backscattering Technique.

3.1 Exponential attenuation in dry sand (SiO$_2$)

As we saw before, the neutron intensity is exponentially attenuated by a material (equation (2.3)). The main material that is going to be taken into account in the simulation of NBT is dry sand (SiO$_2$), which is the simplest kind of soil that we can consider. The colombian soil is a combination of sand (> 60%), clay and silt but this kind of soil is not considered in the present work. However the technique response is expected to be similar, considering only sand, due to the fact that other components of the soil are heavy elements and the main difference will be due to the capacity of the soil to retain water (saturation moisture content) as we will see in the next chapter.

For compounds and mixtures, the total absorption coefficient may be calculated using Bragg’s rule [7]:

$$\frac{\mu}{\rho} = \sum_i w_i \frac{\mu_i}{\rho_i},$$

(3.1)
Figure 3.1: Neutron cross sections for $^{28}\text{Si}$ and $^{16}\text{O}$ as function of the neutron energy [10]. In almost all the energy range the main interaction is elastic scattering. At neutron energies of $E \sim 1$ MeV, the total cross section presents resonances in both cases. The capture cross section increases as the neutron energy decreases.

<table>
<thead>
<tr>
<th>$E$ (MeV)</th>
<th>$\sigma_{\text{Si}}$ (b)</th>
<th>$\sigma_{\text{O}}$ (b)</th>
<th>$\mu_{\text{SiO}_2}$ (cm$^{-1}$)</th>
<th>$\lambda = 1/\sigma_{\text{SiO}_2}$ (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 MeV</td>
<td>4.65</td>
<td>8.15</td>
<td>0.31</td>
<td>3.17</td>
</tr>
<tr>
<td>0.025 eV</td>
<td>2.16</td>
<td>3.97</td>
<td>0.15</td>
<td>6.66</td>
</tr>
</tbody>
</table>

Table 3.1: Attenuation coefficients for dry sand $\mu_{\text{SiO}_2}$ (calculated with eq. (3.3)) and mean free paths $\lambda = 1/\sigma_{\text{SiO}_2}$ for two different neutron energies. The cross sections $\sigma_{\text{O}}$ and $\sigma_{\text{Si}}$ are taken from [10].

where $w_i$ is the weight fraction of the $i$th element in the compound, defined as:

$$w_i = a_i \frac{A_i}{A},$$

with $a_i$ and $A_i$, the number of atoms and the atomic weight of the $i$th element in the compound respectively, and $A$ the molecular weight. In the case of dry sand ($\text{SiO}_2$) we get:

$$\mu_{\text{SiO}_2} = \frac{\rho_{\text{SiO}_2} N_A}{A_{\text{SiO}_2}} (2\sigma_{\text{O}} + \sigma_{\text{Si}}),$$

where $\sigma_{\text{O}}$ and $\sigma_{\text{Si}}$ are the total cross sections for Oxygen and Silicon respectively, which depend on the neutron energy (see Figure 3.1), $\rho_{\text{SiO}_2} = 1.5$ g/cm$^3$ and $A_{\text{SiO}_2} = 60$ g/mol. Table 3.1 shows the cross section, attenuation coefficient and mean free path for two cases: thermal neutrons ($E = 0.025$ eV) and fast neutrons ($E = 1$ MeV).

Table 3.1 shows that the cross sections for neutrons with $E = 1$ MeV are larger than the cross sections for neutrons with $E = 0.025$ eV and therefore the probability to interact with $\text{SiO}_2$, in average, is larger for neutrons with energy $E = 1$ MeV. Another way to see this is found by looking to the mean free path, which for neutrons with initial energy $E = 1$ MeV is approximately twice smaller than the mean free path for thermal neutrons (Table 3.1). This means that the intensity of a thermal neutron beam will be reduced to approximately 36% of its initial value after having traveled 6.6 cm in dry sand while for fast neutrons this reduction of intensity is obtained in 3.17 cm of dry sand (equation (2.3)) and therefore, thermal neutrons will travel further in dry
3.1. EXPONENTIAL ATTENUATION IN DRY SAND ($\text{SiO}_2$)

Figure 3.2: Mean free path in $\text{SiO}_2$ defined as $\lambda_{\text{SiO}_2} = 1/\mu_{\text{SiO}_2}$ as function of the neutron energy. In the fast region ($E \sim 1$ MeV) the mean free path changes in a small energy interval due to resonances in the cross sections (see Figure 3.1). The attenuation coefficient $\mu_{\text{SiO}_2}$ is given by equation (3.3).

sand than fast neutrons. However the cross section for fast neutrons was shown for a particular value of $E = 1$ MeV. In the fast region, there are several resonances in the cross section both for $^{28}\text{Si}$ and $^{16}\text{O}$ (see Figure 3.1). The mean free path, which depends on the cross section, presents resonances in that region too (see Figure 3.2). The values of the interaction probability and therefore the mean free path values can change drastically in that energy region. The exponential attenuation of a neutron beam is important at NBT. As we will see in Chapter 4 in order to detect a hydrogen-rich object fast and thermal neutrons will have to travel certain distance in the sand. If the object is deeper into the sand the survival probability will decrease with depth making difficult to detect it.

3.1.1 Exponential attenuation using Geant4.

Figure 3.3: Set-up implemented in the Geant4 simulation to measure the attenuation coefficient of a monochromatic neutron beam ($N_0$ incident neutrons) in a cubic SiO$_2$ target of width $x$. 

$E = 0.025$ eV
Figure 3.4: Geant4 simulation of the survival probability ($N/N_0$) as function of the target width for two different initial energies. The points are the results of simulation and the lines are the functions in eq. (3.5) resulting from the fit from where the attenuation coefficients (eqs. (3.8) and (3.9)) are calculated.

Figure 3.3 shows the set-up implemented in the Geant4 simulation to calculate the attenuation coefficients in dry sand. A total of $N_0 = 10^4$ neutrons, for two different initial energies $E = 1$ MeV and $E = 0.025$ eV, hit a cubic SiO$_2$ target of width $x$. The neutrons that go through the target without any interaction reach the detector with the same initial energy. The number of detected neutrons ($N$) over the number of initial neutrons ($N_0$), defines the survival probability,

$$P = \frac{N}{N_0}, \quad (3.4)$$

which for a parallel and monoenergetic neutron beam is (see equation (2.3)):

$$P = \exp (-\mu x), \quad (3.5)$$

Figure 3.4 shows the simulated survival probability of a monoenergetic neutron beam traversing the SiO$_2$ target as function of $x$. The number of detected neutrons $N$ is defined in the simulation as the number of neutrons that reach the detector with energies in the interval (see Section A.4):

$$[0.9, 1] \text{ MeV} \rightarrow \text{ for } E = 1 \text{ MeV}, \quad (3.6)$$
$$[0.02, 0.03] \text{ eV} \rightarrow \text{ for } E = 0.025 \text{ eV}. \quad (3.7)$$

The fit of the simulated values of $N/N_0$ to an exponential function of the form (3.5) gives as a result the attenuation coefficients:

$$\mu_{\text{SiO}_2}^{(\text{Fit})}(E = 1 \text{ MeV}) = 0.308(2) \text{ cm}^{-1}, \quad (3.8)$$

$$\mu_{\text{SiO}_2}^{(\text{Fit})}(E = 0.025 \text{ eV}) = 0.153(1) \text{ cm}^{-1}, \quad (3.9)$$

which are in agreement with the theoretical calculations (see Table 3.1).
3.2 Thermalization in a hydrogen target

One of the features of the thermalization process is that in a hydrogen target a neutron beam will require less collisions to reach thermal energies than in heavier targets (see Section 2.1.1). In order to calculate the number of collisions a neutron will require to reach thermal energies with the simulation, a monoenergetic \( E = 1 \text{ MeV} \) isotropic neutron source \( N = 2 \times 10^3 \) neutrons is placed in the center of a cube of side \( L = 2 \text{ m} \) filled with \( \text{H}_2 \). Counting the number of collisions an emitted neutron takes to go from the initial energy \( E_0 = 1 \text{ MeV} \) to final energy \( E = 0.025 \text{ eV} \) the histogram shown in Figure 3.5 is obtained. The simulated data are fitted to a gaussian function obtaining as centroid of the distribution of the number of collisions:

\[
\bar{n} = 17.6(1).
\]  

This value is in agreement with the calculated in equation (2.15) \( \bar{n} = 17.5 \). This equation is an approximation to get the average number of collisions a neutron will require to go from one particular initial energy to a final energy. The obtained distribution (Figure 3.5) show us additionally that the number of collisions to thermalize a neutron beam in a hydrogen target follows a gaussian behaviour with an standard deviation of \( \sigma_n = 4.20(9) \) collisions.

3.3 Interactions in a \(^3\text{He}\) detector

As we saw in Section 2.2 a proton and a triton are produced in the interaction that takes place inside the \(^3\text{He}\) detector (equation (2.16)). In order to check the validity of the models used in the simulation of the \( n(p,^3\text{H})^3\text{He} \) reaction and the energy loss of the charged particles produced,
CHAPTER 3. NEUTRON PHYSICS WITH GEANT4

Figure 3.6: (a). Simulation geometry: the incident neutron position $x_i$ is chosen from a uniform random distribution between $x = -R$ and $x = R$ where $R = 1.25$ cm is the active radius of the detector. The number of incident thermal neutrons is $N_0 = 1000$. (b). Simulated neutron spectrum obtained with this geometry, and the one obtained experimentally (see Section 4.3).

Table 3.2: Characteristics of the neutron detector LND 252228 [11]. The maximum FWHM is given for the thermal peak.

<table>
<thead>
<tr>
<th>Composition</th>
<th>75% $^3$He+25%Ar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas Pressure (atm)</td>
<td>5.0</td>
</tr>
<tr>
<td>Cathode material</td>
<td>Stainless Steel 304.</td>
</tr>
<tr>
<td>Effective length (cm)</td>
<td>20.0</td>
</tr>
<tr>
<td>Effective radius (cm)</td>
<td>1.25</td>
</tr>
<tr>
<td>density (g/cm$^3$)</td>
<td>$0.79 \times 10^{-3}$</td>
</tr>
<tr>
<td>Maximum FWHM</td>
<td>7%</td>
</tr>
</tbody>
</table>

Geant4 is used to simulate the response function of a cylindrical neutron detector following the characteristics of the ones available in the laboratory (see Table 3.2). The particular physics models implemented in the Geant4 simulations are listed in Appendix A.

Within the simulation, a neutron beam with initial energy $E = 0.025$ eV and random initial position with respect to the center of the cylindrical detector, enters the $^3$He detector as is shown in Figure 3.6(a). If the neutron is captured (the reaction takes place), the reaction products deposit energy in the detector by ionization. The total deposited energy is accumulated for each event obtaining the spectrum shown in Figure 3.6(b) Figure 3.6 shows the comparison of the experimental and simulated spectra. We can see that the main characteristics of the neutron spectrum such as the thermal peak at $E = 0.764$ MeV and the wall effect tail, are reproduced and are in agreement with the experimental spectrum. In Section 4.3, it will be described in what
3.3. INTERACTIONS IN A $^{3}$HE DETECTOR

conditions the experimental spectrum was obtained.

### 3.3.1 Fast neutron and gamma-ray interactions

$^{3}$He-based detectors can be used also to detect fast neutrons ($E \approx 1$ MeV) [6]. The cross section of the capture reaction (equation 2.16) is very low compared with the one at thermal energies (see Figure 2.2) and in fact the cross section for elastic scattering is larger than the capture cross section (see Figure 3.7). Therefore the efficiency to detect fast neutrons is lower than the thermal neutron case.

If a fast neutron with initial energy $E_{0}$ is captured inside the $^{3}$He detector the available energy shared among the reaction products (proton and triton) is:

$$E = E_{0} + Q.$$  

(3.11)

As in the thermal neutron case, if the products are completely stopped inside the detector, a peak at $E = E_{0} + Q$ will be observed in the spectrum (see Figure 3.8). This peak is known as the total absorption peak. Besides this peak and its corresponding wall effect tail, it will appear in the spectrum a continuous distribution that comes from elastic scatterings of the fast neutron with the $^{3}$He nuclei. The $^{3}$He recoil nuclei produced by the elastic scattering deposit their energy inside the detector by ionization. The energy of a $^{3}$He recoil nucleus after one collision can be calculated from kinematics as:

$$E_{R} = E_{0} \frac{4A}{(A+1)^{2}} \cos^{2}(\phi),$$

(3.12)
\[ E_{\text{dep}} = 0.75E_0 = 0.975 \text{ MeV} \]

\[ E_{\text{dep}} = E_0 + Q = 2.06 \text{ MeV} \]

Figure 3.8: Simulated response function for $^3$He neutron detector to a monoenergetic fast neutron beam with initial energy $E_0 = 1.3$ MeV. The peak at $E = E_0 + 0.764$ MeV = 2.064 MeV is produced when both products (proton and triton) are completely stopped inside the detector (total absorption peak). The maximum recoil distribution is located around $E_{R\text{max}} = 0.75E_0 = 0.975$ MeV.

where $\phi$ is the scattering angle of the target (see Figure 2.1) and $A$ is the atomic weight of the target. In the case of a $^3$He target we have $A = 3$. The maximum energy a $^3$He recoil nucleus could have after one elastic collision with a fast neutron of initial energy $E_0$ is obtained when this nucleus comes out in the same direction than the incoming neutron ($\phi = 0$):

\[ E_{R\text{max}} = 0.75E_0. \]  \hspace{1cm} (3.13)

Figure 3.8 shows the simulated spectrum obtained when a neutron beam with initial energy $E_0 = 1.3$ MeV enters in a cylindrical $^3$He detector in a similar way as the shown in Figure 3.6 (a). Experimentally we can not obtain a spectrum like the one shown in Figure 3.8, because we do not have a monoenergetic fast neutron source. The source available in the laboratory is a spontaneous fission neutron source of $^{252}$Cf. The neutron energy distribution of this kind of source follows [7]:

\[ \frac{dN}{dE} = \sqrt{E} \exp(-E/T). \]  \hspace{1cm} (3.14)

Experimentally a $^{252}$Cf neutron source has $T = 1.3$ MeV [6]. The neutron energy spectra is simulated with help of a Geant4 class in which it is defined an isotropic source following the spontaneous fission distribution given in equation (3.14) (see Appendix A). As a result we have a neutron source with the energy spectrum shown in Figure 3.9. The simulated data are fitted to a function of the form given in equation (3.14) obtaining

\[ T_{\text{sim}} = 1.27(1) \text{ MeV}. \]  \hspace{1cm} (3.15)

If a $^3$He neutron detector is exposed to a fast neutron source with a continuous energy spectrum
3.3. INTERACTIONS IN A $^3$He DETECTOR

![Figure 3.9: Geant4 simulation of the neutron energy spectrum of a $^{252}$Cf spontaneous fission neutron source. The points are the result of the simulation and the dotted line is the result of the fit of these data to the function in equation (3.14).](image)

like the shown in Figure 3.9, a continuous background will be obtained as a result of the sum of individual spectra for each neutron energy like the shown in Figure 3.8. Each individual spectra will have total absorption peaks at different positions and different $^3$He recoil nuclei distributions depending on the initial neutron energy. This background produced by fast neutrons is simulated in Geant4 and shown in Figure 3.10. The maximum of the fast neutron background will be located at low deposited energies, as a result of the sum of all the recoil nuclei distributions (Figure 3.8).

In addition to the fast neutron interactions, $\gamma$-rays can produce a background too. These $\gamma$-rays come from different sources such as:

1. Natural radioactivity.
2. Neutron source itself.
3. Thermal neutron capture reactions with the surrounding materials.

Neutron sources such as $^{252}$Cf produce $\gamma$-rays together with the spontaneous fission process with energies in the order of MeV [12]. On the other hand, once a fast neutron has been thermalized the probability to be captured by a nucleus increase (see Figure 3.1). In this capture reaction the target nucleus could be left in an excited state decaying later by $\gamma$-ray emission. Whatever the source is, $\gamma$-rays can interact with the gas inside the detector or with its metallic walls through Compton scattering or photo-electric effect. These interactions produce electrons that deposit their energies in the detector by ionization. Figure 3.10 shows the different contributions in a $^3$He detector like the ones we have in our laboratory. In the next Chapter the geometry implemented in the simulation to obtain this spectrum will be described.
Figure 3.10 shows that γ-ray interactions yield to a low energy tail, however low energy counts increase experimentally due to electronic noise in the detector. On the other hand, deposited energies above the thermal peak located in $E = 0.764$ MeV, can be interpreted as fast neutron interactions.

As we will see in the next chapter the main quantity that is going to be measured is NBT is the number of thermal neutrons that reach the detector. This can be obtained by integrating the spectrum due only to thermal neutron interactions (see Figure 3.10). However experimentally we can not discriminate the different contributions in the obtained spectrum. If we assume that during the time the data is taken the γ-ray as well as the fast neutron background do not change, the integral of the entire spectrum will be proportional to the number of thermal neutrons that reached the detector. However the electronic noise can change within this time. The only way we have to avoid some of this noise and some of the γ-rays background is to set a threshold channel in the measured spectrum. The counts below this threshold will not contribute to the total spectrum. If we set a threshold at the channel corresponding to 0.2 MeV in the spectrum shown in Figure 3.10, it is seen that the major part of the γ-ray background together with some of the fast neutron background can be avoided. Calculating the integral of the total spectrum and thermal spectrum above this threshold, it is concluded that 77% of the total counts are due to thermal neutron interactions. The total number of thermal neutrons that reached a detector important at NBT (see next chapter), will be calculated in the simulated and experimental spectrum as the counts above the channel corresponding to 0.2 MeV.
Chapter 4

The Neutron Backscattering Technique

The main features of neutron-matter interaction have been described in the previous chapters. Now, these features are mixed together to describe NBT in order to detect hydrogen-rich objects. This chapter begins with the description of the NBT set-up and continues with the data analysis implemented to get an approximate value of the place where the hydrogen-rich object is placed. In the second part the Geant4 simulation results of this technique are presented. It is shown how the response of the technique is affected by several geometrical parameters and how this response changes by including moisture in the soil. Finally the experimental results obtained at the laboratory are shown.

4.1 NBT set-up and data analysis

The Neutron Backscattering Technique is based on the fact that hydrogen-rich objects are media where fast neutrons can reach thermal energies in a more efficient way (less collisions) than in targets composed by heavier nuclei. This feature was shown in section 2.1.1. Different approaches have been studied to implement this phenomenon in a device capable of detecting hydrogen-rich objects [1, 3, 13]. In this work we follow the set-up and data analysis proposed by Brooks [1]. The NBT set-up implemented in this work is shown in Figure 4.1. Eight cylindrical neutron detectors ($^3$He+Ar), distributed in two arrays (labeled as $A$ and $B$), and a fast neutron source ($^{252}$Cf) are placed above a sand (SiO$_2$) box in which the object to be detected, is buried. The detector arrays $A$ and $B$ and the neutron source move together along a path parallel to the soil surface ($x$ coordinate). The fast neutrons emitted by the source interact with the soil and with the buried object mainly by elastic collisions. This is because the cross section for elastic scattering is larger than the cross sections for other interactions (see Figure 3.1). In this process the incoming fast neutrons lose energy and as we saw in section 2.1.1 if the buried object is hydrogen-rich the number of thermal neutrons will increase as the detector system (source and detectors) approaches to it.

Each neutron detector follows the response shown in Figure 3.10. As was mentioned in Section 3.3.1 the main quantity that is going to be measured in NBT is the number of thermal neutrons
CHAPTER 4. THE NEUTRON BACKSCATTERING TECHNIQUE

Figure 4.1: Neutron Backscattering Technique set-up for the detection of a buried hydrogen-rich object. The green line represents a neutron being emitted by the source, interacting with the soil, with the buried object and finally being detected at detector 1.

Figure 4.2: Expected response of a scan with the NBT set-up (Figure 4.1) for an hydrogen-rich object located in $x_0$. $A(x)$ and $B(x)$ are the signals in the corresponding detector arrays.
4.1. NBT SET-UP AND DATA ANALYSIS

Figure 4.3: The maximum number of thermal backscattered neutrons is found in the $x$ position where the center of the hydrogen-rich object is located at midway between the source and the detector (see Figure 4.2, the maximum is located in $x = x_0 - s$ for the $A$ array and in $x = x_0 + s$ for the $B$ array.)

that reached the detector. Setting a threshold channel in the spectrum at each detector (in this case at the channel corresponding to 0.2 MeV) and calculating the total number of counts above this threshold we get a number of counts proportional to the number of detected thermal neutrons. The procedure to detect the buried object consists first in measuring this number of counts in each detector array as function of the $x$ coordinate. The expected response of this scan is shown in Figure 4.2. The number of thermal neutrons increases in positions near the hydrogen-rich object ($x = x_0$) due to the thermalization process. The maximum of each distribution happens when the center of the object is at midway between the source and the detector: There is compromise between the source-object distance and the detector-object distance. The probability a fast neutron has to thermalize in the object and be scattered in the direction of the detector is larger when these two distances are almost equal (see Figure 4.3).

If the arrays signals $A(x)$ and $B(x)$, which in principle follow a gaussian behaviour, are subtracted, we get the difference function $D(x) = A(x) - B(x)$ (see Figure 4.2). The position $x_0$ in which $D(x_0) = 0$ and $D(x)$ goes from positive to negative values, marks the position in which the hydrogen-rich object is buried [1]. The signal functions $A(x)$ and $B(x)$ as well as the counts difference $D(x)$ will depend on parameters such as:

- Stand-off distance ($z$ in Figure 4.1).
- Arrays separation distance ($a$).
- Depth of the target ($d$).
- Amount and composition of the hydrogen-rich object.
- Acquisition time.
- Moisture content in soil.

The influence of some of these parameters in the detection method has been studied in [1, 3, 13]. In [3], a single $20 \times 20$ cm$^2$ multi-wire proportional chamber (MWPC) is used as detector. With a $^{252}$Cf ($5 \times 10^4$ n/s) it is studied the behaviour of the total number of registered counts as function of parameters such as the stand-off distance and the weight of a high density polyethylene sample used as target. This is done with the detector placed in a fixed position above the buried
CHAPTER 4. THE NEUTRON BACKSCATTERING TECHNIQUE

TNT Simulant → [H:C:N:O] = [5:7:3:6]

Acrylic → [H:C:N:O] = [4:2:0:1]

Figure 4.4: Dimensions (in cm), elemental composition and picture of the dummy mine DLM2 used in the simulated and experimental set-up of NBT. The [H:C:N:O] bracket refers to the number of atoms in the molecule that compose the material.

In [13] experimental results are shown using a single $^3$He detector covered by a combined reflector-shielding (Carbon-Borated paraffin). Linear scans are made for two different land mines but the behaviour on the total number of counts as function of the stand-off distance, reflector dimensions, mine depth and neutron energy is shown in the majority of cases without an scan but with the detector again in a fixed position. In the present work, following [11], all the analysis will be done starting from the data taken in several scans over the soil.

On the other hand, if a single detector is used in NBT a strong dependence on the stand-off distance is obtained i.e small movements (in the order of cm) in the detector height above the soil (parameter $z$ in Figure 4.1) produce large counts differences that could mimic the signal of a buried object. That is why it was proposed to use two neutron detectors separated certain distance (parameter $a$ in Figure 4.1). If the signals at each detector are subtracted the dependence on the stand-off distance can be minimized [13].

In the HYDAD-D (HYdrogen Anomaly Detector) set-up, proposed by Brooks [1], two $^3$He detectors are used. In the set-up we use in the present work, eight neutron detectors are organized in two arrays: $A$ and $B$ (see Figure 4.1). The extra detectors are included to increase the sensitive area.

4.2 Geant4 simulation of NBT

The first method to study NBT in the present work is the simulation of the technique using the tool-kit Geant4 [9]. The set-up implemented in the simulation is the one shown in Figure 4.1. The soil composition is dry sand ($\text{SiO}_2$) with density $\rho = 1.5 \text{ g/cm}^3$. The dimensions and materials of the detectors are chosen following the characteristics of the ones we have in our laboratory (see Table 3.2). The neutron source (252Cf) follows the characteristic neutron energy spectrum of a spontaneous fission process (see Figure 3.9). As we will see in Section 4.3 there are additional objects in the laboratory which were included in the simulation (the wood box, a concrete column and a paraffin shielding. See Appendix A). The hydrogen-rich object is a dummy-mine (DLM2) provided by Andy Buffler of the University of Cape Town [14]. It consists of 100 g of a TNT simulant inside an acrylic (polymethylmethacrylate) container (see Figure 4.4). This target is also used at the laboratory tests (see Section 4.3).
Figure 4.5: Geant4 simulation of NBT for the DLM2 as test object placed at the surface of the sand box (\(d = 0\) cm) and at \(x = 0\) cm. The points are the simulation results and the lines are the fits to the functions in eqs. (4.1) and (4.2).

Figure 4.5 shows the result of a scan of the NBT set-up (see Figure 4.1 and Appendix A), with the DLM2 as a test object placed at a depth of \(d = 0\) cm and at \(x = 0\) cm. A total of \(N = 2.3 \times 10^6\) neutrons are emitted from the source for each \(x\) position in steps of \(\Delta x = 5\) cm. The number of counts for each array as function of the \(x\) coordinate (\(A(x)\) and \(B(x)\)) is fitted to the function:

\[
G_i(x) = Y_i \exp\left(\frac{(x - x_i)^2}{2\sigma_i^2}\right) + B_i x + C_i, \quad (4.1)
\]

where the last two terms describe a non-flat background and the subindex \(i\) refers either to the \(A\) or \(B\) array. The counts difference \(D(x)\) is fitted to the difference of two identical gaussians.
displaced a quantity $2s$ (see Figure 4.2):

$$D(x) = D_0 \left( \exp \left( \frac{(x - x_0 - s)^2}{2\sigma_0^2} \right) - \exp \left( \frac{(x - x_0 + s)^2}{2\sigma_0^2} \right) \right) + B_0,$$

(4.2)

where $B_0$ is included to allow differences in the background at the detector arrays and the parameter $x_0$ is the $x$ position in which the hydrogen-rich object is buried.

For the DLM2 placed at $d = 0$ cm and at $x = 0$ cm the fit of the difference function $D(x)$ (equation (4.2)) to the simulated results (see Figure 4.5), gives as a result the following parameters:

$$D_0 = 5.9(7) \times 10^2 \text{ counts},$$

$$x_0 = 0.5(6) \text{ cm},$$

$$\sigma_0 = 5.4(5) \text{ cm},$$

$$s = 2.4(2) \text{ cm}.$$ (4.3)

The parameter $x_0$ in this case gives a good prediction of the $x$ position of the DLM2. The parameters in equation (4.3) change as function of the geometrical parameters previously mentioned (stand-off distance, depth, etc.) For example, Figure 4.6 shows the dependence of the NBT response to changes in the depth $d$. The number of counts decreases as the DLM2 go deeper into the sand box as expected: the number of neutrons thermalized in the DLM2 region will be exponentially attenuated in their way back to the detectors. The survival probability decreases as the thickness of sand the neutrons have to go through, increase (see Figure 3.4). At a depth of $d = 10$ cm the difference function $D(x)$ present a constant behaviour (Figure 4.6) i.e $D(x) \approx 0$ in the whole $x$ range and therefore the object is not detected at this depth. Looking at the detector signal $A(x)$ at this depth, there is differences with respect to the distribution obtained with no buried object (see Figure 4.6). As we will see in Section 4.3 and Chapter 5, the decision about having a buried object or not is going to be composed by several steps such as the shape of the functions $A(x)$, $B(x)$ and counts difference $D(x)$ and the inclusion of a detection parameter related to the amplitude $D_0$ resulting from the fit.

Figure 4.7 shows the behaviour of the difference function for different stand-off distances $z$. The amplitude $D_0$ of the distribution decreases with $z$. At $z = 13$ cm a flat distribution is obtained (the object is not detected). The number of thermal neutrons detected decrease with $z$ because the number of fast neutrons that arrives to the DLM2 decrease with increments in $z$ (see Figure 4.8).

### 4.2.1 NBT including moisture in the soil

An important parameter to take into account in NBT is the percentage of moisture content in the soil, defined as:

$$\theta = \frac{m_{H_2O}}{m_{Soil}},$$

(4.4)

where $m_{H_2O}$ is the mass of water present in the soil, and $m_{Soil}$ is the mass of the solid phase of the soil. The additional hydrogen content in the environment at which the hydrogen-rich object is buried, yields to a thermal neutron background that could screen its presence [5]. Although it is
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Figure 4.6: (a) Total counts in the A array ($A(x)$) and (b) counts difference ($D(x)$) for different depths $d$ (see Figure 4.1). The DLM2 is placed at $x = 0$ cm and the detectors are at $z = 3$ cm. In the $d = 10$ cm case differences with respect to the background (no object) are obtained for $A(x)$ but not for $D(x)$.

It is known that the moisture content may be a problem in the use of NBT for the detection of organic materials [3, 5], no simulations nor experiments have been performed using the difference method (Section 4.1). In [5] a theoretical calculation is made to determine the critical moisture value at which a landmine can not be detected. At this critical moisture value the number of backscattered thermal neutrons that come from the buried object is equal to the number of thermal neutrons produced by the wet soil and therefore no signal is obtained above the background. In the Geant4 simulation in the present work, moisture is included in the soil in different per-
Figure 4.7: Counts difference for different stand-off distances $z$ (see Figure 4.1). The DLM2 is placed at $x = 0$ cm and at $d = 0$ cm. For $z = 13$ cm, $D(x) \approx 0$ in the whole $x$ range.

Figure 4.8: The solid angles $\phi$ and $\theta$, are inversely proportional to $z$ and $d$. More thermal neutrons will arrive to the detectors in the case b because $\phi_1 < \phi_2$ and $\theta_1 < \theta_2$ ($b_1 > b_2$ and $z_1 > z_2$).

centages by weight ($\theta$), to study its influence on NBT. Table 4.1 shows the hydrogen density for different materials used in the simulation. The TNT simulant and acrylic compose the DLM2 used (see Figure 4.4). Table 4.1 suggests that a moisture content of $\theta = 15\%$ the DLM2 may be detected because the hydrogen densities of the acrylic container and TNT are larger. Most of the new built landmines have plastic coverings that help to its detection because they are hydrogen-rich materials [5].

To determine the critical moisture value using NBT for the DLM2 several simulations and experiments (see Section 4.3) were made in the present work. Figure 4.9 shows the simulation of NBT for different moisture values. The DLM2 is placed at the surface of the wet soil ($d = 0$ cm).
Material  | #H/cm\(^3\) \(\times 10^{22}\) | \(\rho\text{ (g/cm}^3\) | 
--- | --- | --- | 
Acrylic | 6.29 | 1.15 | 
TNT Simulant | 2.18 | 1.65 | 
Dry Sand (SiO\(_2\)) | 0 | 1.5 | 
Sand (5% water) | 0.53 | 1.58\(^{(a)}\) | 
Sand (10% water) | 1.11 | 1.66\(^{(a)}\) | 
Sand (15% water) | 1.75 | 1.74\(^{(a)}\) | 
Sand (50% water) | 7.69 | 2.30 | 

\(^{(a)}\): Taken from [15]

| Table 4.1: Characteristics of the materials used in the simulation.

The increment in the moisture content produce more thermal neutrons as background. The measurement of the number of counts far away from the object \((x \approx 20\text{ cm})\) or equivalently the parameters \(C_i\) resulting from the fit (equation 4.1) gives a direct measurement of the moisture content in the soil [16].

Looking at the difference function \(D(x)\) (Figure 4.9b) at 15% of moisture content \(D(x) \neq 0\) in the whole \(x\) range and a small increment of the amplitude, although not symmetric, is observed. The simulation of the moisture dependence of NBT at \(d = 5\text{ cm}\) is shown in Figure 4.10. The increment in the amplitude of \(D(x)\) in the 0 – 10% moisture range is more noticeable than the case at \(d = 0\text{ cm}\) (see Figure 4.9).

This increment in the amplitude and therefore in the number of backscattered thermal neutrons, produced by the DLM2, can be explained as a pre-thermalization process: fast neutrons coming into the wet sand will lose energy by elastic collisions with the Hydrogen nuclei (protons) of the present water before entering into the DLM2 region. At this stage the neutrons begin to interact with the DLM2 with less energy, in average, than the dry sand case. Neutrons with less energy will require less collisions to thermalize (equation 2.14). This energy loss process in the soil before the thermalization process in the hydrogen-rich object which has larger Hydrogen density (see Table 4.1), produces the increment in the number of detected thermal neutrons.

In order to test this last hypotesis within the simulation, the energy spectra of the neutrons entering and leaving the DLM2 region is presented in Figure 4.11. More low energy neutrons enter the DLM2 region in the wet sand case than in the dry sand case Figure 4.11a. This is expected due to the hydrogen present in the water surrounding the DLM2. Looking at the energy spectra of the neutrons leaving the DLM2 region (Figure 4.11b) it is seen that more low energy neutrons are produced in the wet sand case than in the dry sand case (pre-thermalization).

At larger moisture values the amplitude \(D_0\) begins to decrease (Figure 4.10 at \(\theta = 15\%\)). Figure 4.12 shows the result of simulating the NBT response at a moisture of 50%. In this case the Hydrogen density is larger in the soil than in the DLM2 (see Table 4.1) and less neutrons are thermalized in it than in the surrounding soil. A decrement in the number of detected thermal neutrons is therefore observed (see Figure 4.12a). This produces an inverse difference function (Figure 4.12b) which in principle can also be used to determine the position of the hydrogen-rich
Figure 4.9: (a): Simulated $A(x)$ distribution for different moisture values ($d = 0 \text{ cm}, z = 3 \text{ cm}$). The number of counts far away from the buried object ($x \approx 20 \text{ cm}$), with the proper calibration, gives a measurement of the moisture content in the soil. (b): Simulated counts difference $D(x)$ for the corresponding values in (a). Small differences, although not symmetric, are observed in the amplitude $D_0$ as the moisture content increases.
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Figure 4.10: Simulated distribution $D(x)$ for different moisture values ($d = 5$ cm). In this case it is clear that the amplitude of $D(x)$ increase with the moisture content in the $0 - 10\%$ range.

Figure 4.11: Energy spectra of the neutrons entering (a) and leaving (b) the DLM2 region.

object. Moisture contents in different types of soils depend on their physical properties such as grain size, chemical composition, etc [17]. There is a saturation moisture value ($\theta_{\text{sat}}$) at which the soil does not retain more water and it begins to drain. For sand ($\text{SiO}_2$) for example the saturation moisture value is between 20% and 25% depending on the grain size [17]. Although moisture values in sand larger than this values can not be experimentally obtained, the simulation is done at 50% of moisture as a test. This high moisture values can be easily reached in other kind of soils [17].

Figure 4.13 shows the evolution of the relative amplitude $D_0/D_0(\theta = 0\%)$ as a function of the moisture content $\theta$ for the DLM2 placed at $d = 0$ cm. In the $0 - 10\%$ moisture range there is an increment with a maximum at around $\theta = 10\%$. At larger moisture values the relative amplitude begins to decrease until almost zero at $\theta = 42\%$. This value is the critical moisture value at which
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Figure 4.12: NBT simulation results including soil moisture of $\theta = 50\%$ for the DLM2 placed at $d = 0$ cm. (a) Simulated $A(x)$ and $B(x)$ and (b) counts difference $D(x)$. At high moisture values the distributions are inverted with respect to the expected response (Figure 4.2) and in could be possible to "detect" the buried object.

the DLM2 does not produce an appreciable difference with respect to the background. Using the theoretical approximation for the critical moisture value $[5]$ it is obtained $\theta_{\text{crit}} = 24\%$, which value is smaller than the obtained value at the simulation. This indicates that the theoretical approximation do not describe completely the phenomenon. At moisture values higher than $\theta = 42\%$ negative amplitudes (inverse difference functions) are obtained. This inverse signals, as was said before, could be used, in principle, in the detection technique.
4.3 Experimental Results

The simulation results shown in the previous section gave us the main behaviour of NBT as a function of several parameters such as the depth \(d\), the height \(z\) and the moisture content in the soil \(\theta\). The next step is to study the technique experimentally. In this section there are shown the main experimental results obtained with the instrumentation of the laboratory at the Nuclear Physics group in the Universidad Nacional.

The experimental set-up to implement NBT is shown in Figure 4.14. It follows the set-up shown in Figure 4.1. A set of eight LND neutron detectors (see Table 3.2) is placed inside a wood box which contains the dry sand where the DLM2 is buried. The detectors are connected to an Mesytec module MSTD-16 (Figure 4.15 a) which provides the high voltage through the NHQ-203M HV supply and collects the signals that come from them. The voltage used in all the tests was 1.3 kV. The data are transmitted from the MSTD-16 to the central processing device MCPD-2 (see Figure 4.15 a) which is the interface with the PC. It has an ethernet output connected to the PC where the Mesydaq software [18] is installed. The software is used to visualize and save the spectra from each detector (see Figure 4.15 b) and to control the MCPD-8 parameters such as gains, thresholds, etc.

The \(^{252}\text{Cf}\) neutron source has an activity of \(1.15 \times 10^5\) n/s. The spectrum shown in Figure 3.6 is the spectrum obtained in detector 1 with the set-up shown in Figure 4.14 \((x = 0\) cm\) and with an acquisition time of \(t = 5\) min. The spectra from the other detectors are similar. No object is buried and therefore the detected backscattered thermal neutrons come from the soil and the wood box. As in the previous section the number of counts in each array is taken as the sum of

\[
\frac{D_0}{D_0(\theta = 0\%)}
\]

\[
\theta(\%)
\]

Figure 4.13: Amplitudes of the \(D(x)\) distributions \((D_0)\) relative to the one obtained with dry sand \((\theta = 0\%)\) as a function of the moisture content \(\theta\). A maximum is obtained at 10% and at larger moisture values the relative amplitude goes through zero (critical moisture value at \(\theta \approx 42\%\)) and then to negative values i.e inverse difference functions (see Figure 4.12).
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Figure 4.14: Experimental set-up of NBT. It follows the set-up shown in Figure 4.1. The position $x$ of the detection system is taken with respect to center of the wood box which contains approximately one ton of dry sand ($1.2 \times 1.2 \times 0.5 \text{ m}^3$) (in this picture the system is located at $x = 0 \text{ cm}$).

Figure 4.15: (a) Mesytec modules MSTD-16, MCPD-2 and HV supply used at the data acquisition for NBT. (b) Screenshot of the Mesydaq software which controls the mesytec modules and shows a visual output of the measured spectra at each detector.
4.3. EXPERIMENTAL RESULTS

Figure 4.16: Simulated and experimental $B(x)$ (a) and $D(x)$ (b) for the DLM2 placed at $d = 0$ cm and $x = 0$ cm. The fitted parameters are listed in Table 4.2.

In order to compare the simulation results of NBT shown in Section 4.2 with the experimental ones obtained with the set-up shown in Figure 4.14, data were taken with an acquisition time of $t = 2$ s per $x$ position in steps of $\Delta x = 5$ cm. Considering the activity of the $^{252}$Cf neutron source ($1.15 \times 10^6$ n/s) this acquisition time is equivalent to the $N = 2.3 \times 10^6$ simulated neutron events per $x$ position. The results are shown in Figure 4.16. As in the previous section the data are fitted to the functions in eqs. 4.1 and 4.2. The fitted parameters are listed in Table 4.2. A good agreement is obtained. This suggests that the main neutrons interactions were taken into...
account in the proper way at the simulation.

**4.3.1 Depth Dependence**

Figure 4.17 shows the experimental results obtained with the NBT set-up (Figure 4.14) using as a test object the DLM2 buried at different depths. The data were taken with an acquisition time of \( t = 60 \) s per \( x \) position in steps of \( \Delta x = 5 \) cm. Figure 4.17 shows that the amplitude of the difference function \( D_0 \) decrease as the DLM2 goes deeper into the sand box as expected due to the exponential attenuation (Section 3.1.1). At a depth of \( d = 15 \) cm the difference function still can be fitted to the function \( D(x) \) obtaining a non-zero amplitude \( D_0 \). This means that the DLM2 could be detected at this depth with an acquisition time of 60 s per position.

**4.3.2 Moisture dependence**

As was mentioned in Section 4.2.1 one of main parameters that has to be taken into account in NBT is the moisture content in the soil. In order to get the behaviour of NBT as function of the moisture content several values of moisture have to be considered. Experimentally it is not easy to wet homogeneously all the sand in the wood box. Besides that, a sample of sand has to be dried first in order to wet it with the next moisture value. An homogeneous drying process for the amount of sand required would take too long time intervals (in the order of weeks). It was considered then to make the measurements including only a wet sand layer of certain width \( w \) (see Figure 4.18), to study the moisture effect on NBT in a more efficient way. Figure 4.19
Table 4.2: Experimental and simulated parameters resulting from the fits to the functions in eqs. 4.1 and 4.2 for $B(x)$ and $D(x)$ (see Figure 4.16). The Geant4 simulation reproduce fairly well the experimental results.

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<th>Sim</th>
<th>Parameter</th>
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<td>$0.6(6)$</td>
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<tr>
<td>$\sigma_B$ (cm)</td>
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<td>$4.3(5)$</td>
<td>$s$ (cm)</td>
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<td>$2.5(3)$</td>
</tr>
<tr>
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<td>$0.3(7)$</td>
<td>$\sigma_0$ (cm)</td>
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<td>$4.5(6)$</td>
</tr>
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<td>$5.5(7) \times 10^2$</td>
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</tbody>
</table>

Figure 4.18: Experimental set-up for NBT including a wet sand layer of width $w$. Shows the result of varying the moisture content for the DLM2 placed at $d = 0$ cm and with a wet sand layer width of $w = 5$ cm. The amplitude of $D(x)$ increases with the moisture as was seen in the simulation (Section 4.2.1). In this case the increment is more noticeable that the simulation one (see Figure 4.9) because the number of neutrons per position is larger and therefore the statistics is better. This increment shows that the pre-thermalization process seen at the simulations is being observed experimentally. Figure 4.20 shows the amplitudes $D_0$ resulting from the fit for the set of parameters $d$, $w$ and $\theta$ used in the experimental set-up. The amplitude decreases with the depth for any combination of ($\theta, w$) due to the exponential attenuation. Figure 4.20 shows also that the amplitude $D_0$ increases at the same depth for different moisture contents. This can be explained as a pre-thermalization process in the wet sand surrounding the DLM2. At the surface ($d = 0$ cm) the amplitude increases to about the same value for different combinations of moisture values $\theta$ and wet sand layer widths $w$. Figure 4.21 shows the result of scans made with more depth values of the DLM2 for different moisture values using a wet sand layer of $w = 18$ cm. This figure shows that the pre-thermalization process, where the amplitude
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Figure 4.19: Counts difference $D(x)$ for the DLM2 placed at $d = 0$ cm for three different moisture values.

Figure 4.20: Experimental difference amplitude $D_0$ as function of the mine depth, for different values of $\theta$ and $w$. At the same depth, $D_0$ increases with $\theta$ and $w$ (see Figure 4.22).

of the signal is larger for the wet sand case than for the dry sand case is seen experimentally. Figure 4.20 shows also that the signal amplitude at $d = 5$ cm not only increases with the moisture content but also at the same moisture, it increases with $w$. This means that the pre-thermalization
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Figure 4.21: Difference amplitude $D_0$ as function of the mine depth, for different values of $\theta$ and a wet sand layer of $w = 18$ cm.

$$D_0(w = 0 \text{ cm}) < D_0(w = 5 \text{ cm}) < D_0(w = 10 \text{ cm})$$

Figure 4.22: The pre-thermalization process depends not only on the moisture content $\theta$ but also on the amount of wet material around the hydrogen-rich object (at the same moisture and depth). The number of thermal backscattered neutrons increases with the amount of wet material ($w$) as it is seen in the parameter $D_0$ in Figure 4.20.

process in the wet sand below the DLM2 is increasing the number of backscattered thermal neutrons (see Figure 4.22).

Figure 4.23 shows the evolution of the obtained amplitude ratios $D_0/D_0(\theta = 0\%)$ as function of the moisture content. The signal amplitude increases in the moisture range $0\% - 10\%$ both for the simulation and for the experiment. Although in the simulation the whole sand volume was wet and not only a wet sand layer, a good agreement is obtained for $d = 0$ cm.

In [19] it is implemented NBT with a single detector and a paraffin shielding. The experimental results are opposite to the ones shown in the present work. In that work the signal amplitude decreases with the moisture content in the same range. This could be due to the shielding presence which produces a high thermal neutron background that somehow screens the pre-thermalization process. The simulation results presented in the present work are supported by the experimental
ones, in which an increment in the number of backscattered neutrons is seen in the moisture range $\theta = 0\% - 10\%$.

As was mention in Section 4.2.1, experiments for dry sand can not be done beyond $\theta \approx 20\%$ because this is the saturation moisture value ($\theta_{sat}$) for this kind of soil. However it can be said that for other kind of soils the detection technique may be possible at high moisture contents by looking at negative values of amplitude ratios i.e by looking for inverted difference functions like the shown in Figure 4.12 in which the number of backscattered thermal neutrons produced by the soil is larger than the produced by the hydrogen-rich object.
Chapter 5

Results with the prototype HYDAD-D

This chapter shows the main results of a particular realization of NBT: The HYdrogen Anomaly Detector (HYDAD-D) developed at iThemba Labs in Cape Town, South Africa [1]. The HYDAD-D set-up (see Figure 5.1) was used in field conditions. Several measurements were taken, first burying the DLM2 (dummy-mine) at known depths and then in a "Mine field" where different hydrogen-rich objects had been buried before. The data are taken using the software tool HYDASCAN (see Appendix B) that gives to the operator a graphical interface as well as different parameters that will help to decide whether a Hydrogen anomaly is detected or not. Details about the results shown in this chapter and some more are found in [20].

5.1 The HYDAD-D set-up

The HYDAD-D set-up is similar to the one implemented in the experimental part of the present work (Figure 4.14). It consists on several components (see Figure 5.1):

1. Two identical $^3$He detectors (LND 254), labeled as $A$ and $B$, with an active radius of $r = 2.5$ cm and active length of $l = 10$ cm.

2. A neutron source. (Am-Be source ($10^7$ n/s))

3. Two modules All-In-One (AIO) which contain the High Voltage supply, the charge-sensitive pre-amplifier and the pulse-height discriminator.

4. The interface to the computer ($\mu$-DAQ-lite + additional electronics) [21].

5. PC with the HYDASCAN software to analyze the data [22].

6. A motor-driven system to keep under control the speed of the source-detector system.

7. A system to measure the device position $x$ (pulley + potentiometer).
CHAPTER 5. RESULTS WITH THE PROTOTYPE HYDAD-D

5.2 The HYDAD-D detection parameter

Having similar experimental set-ups the expected response of the HYDAD-D is similar to the shown in Figure 4.2. The data analysis used in the HYDAD-D includes some more details to define a parameter that may help in the detection process [1]. The experimental counts difference function $D_e(x) = A(x) - B(x)$ defines the signature function:

$$S(x) = \frac{D_e(x)}{\sigma_D},$$

(5.1)

where $\sigma_D = (A(x) + B(x))^{1/2}$ is the standard deviation of $D_e(x)$. The $x$ coordinate is divided into $n$ bins and, in order to improve statistical accuracy, an indicator function is defined as:

$$I(n) = \sum_{i=n-m}^{n+m} S(i),$$

(5.2)

where $n$ is the bin number (position $x$) and $m$ is an integer number that defines the number of bins taken around a defined $n$. Experimentally the scans are made with $m = 3$ but its value can be changed in the acquisition software (Appendix B).

The indicator function $I(n)$, is fitted to the difference of two identical Gaussians displaced a length $2s$ to each other (see Figure 4.2 and equation (4.2)). This fit is done by finding the set of parameters $(D_0, x_0, s, \sigma_0$ and $B_0)$ that minimizes the quantity:

$$M = \sum \frac{(D(n) - I(n))^2}{N_D},$$

(5.3)

where $D(n)$ is the value of $D(x)$ (equation 4.2) calculated in the position $x$ that corresponds to the bin $n$. The sum is taken over all the $N_D$ bins used in the measurement. The quantity $M$
measures the quality of the fit of the experimental data to the function in equation (4.2). The detection parameter is defined then as:

\[ P = \frac{D_0}{M}, \]  

with \( D_0 \) the amplitude of \( D(x) \) resulting of the fitting process. If there is a hydrogen-rich buried object, the amplitude of the signal \( (D_0) \) will be large and if the fit is good, low \( M \) values are obtained leading to larger \( P \) values. On the other hand if there is no buried object, the amplitude of the signal will be small and if the corresponding fit is not good, large values for \( M \) are obtained resulting in low \( P \) values. The final \( P \) value will correspond to a final status of the detection (HYDASCAN light traffic) as:

- Negative ("Green") if \( P < 3 \).
- Ambiguous ("Yellow") if \( 3 < P < 6 \).
- Positive ("Red") if \( P > 6 \).

5.3 Laboratory tests

Several indoor tests were performed to study the HYDAD-D response including an almost constant background (see Figs. 5.2-5.5). All the scans were made with the test object at \( x = 30 \) cm i.e. at mid-way of the scanned path of 60 cm (see Figure 5.1). This initial position of \( x = 30 \) cm corresponds to the \( x_0 \) position shown in Figure 4.2. The tests objects are placed above a lucite plate to simulate a constant background. The presence of a hydrogen-rich object like the DLM2 produces a well defined signature that gives a larger \( P \) value (Figure 5.2) and therefore the scan finishes with a positive red status. When there is no object present a flat signature and negative final status \( (P < 1) \) is obtained as expected (Figure 5.3).

The HYDAD-D can be used also to confirm the presence of a Hydrogen anomaly in a position previously marked by a different and independent detector. This is why all the scans are made with the object at the middle of the scanned path. However in order to evaluate the capability of the detector when the previous mark place is not well defined, one test was made by changing the position of the hydrogen-rich object to a shifted position, a few centimeters away from the center of the scanned path \( (x = 30 \) cm). It can be seen that part of the signature appears on the screen (Figure 5.4) when the paraffin cylinder, used as a test object, is shifted 20 cm off the center \( (x = 50 \) cm). The software needs to have a complete signature in order to do the corresponding fit and therefore in this case the final \( P \) value is low and an ambiguous final status is obtained. When the paraffin cylinder is closer to the center, e.g. shifted 12 cm \( (x = 42 \) cm), a complete signature appears making the \( P \) value larger (Figure 5.5) and leading to a positive final status. The hydrogen-rich object in this case, although off the center of the scanned path, produced a complete signature. The HYDAD-D user for example can decide to move the detector if it is predicted that a complete signature may be obtained by doing so.
CHAPTER 5. RESULTS WITH THE PROTOTYPE HYDAD-D

Figure 5.2: HYDAD-D set-up and HYDASCAN display for a scan over a dummy-mine (DLM2) located at $x = 30$ cm. The top plot at the display (right) shows the $A(x)$ distribution in pink, the $B(x)$ distribution in blue, $I(n)$ in black and the corresponding function resulting of the fit $D(x)$ in red. The bottom plot shows the value of the detection parameter $P$ as function of the total number of counts $N$ (see Appendix B). In this case $P > 6$ and therefore is obtained a red (positive) final status.

Figure 5.3: HYDASCAN display of a scan with no object present. In this case a flat signature is obtained, $P < 3$ and therefore is obtained a green (negative) final status.
5.3. LABORATORY TESTS

Figure 5.4: HYDASCAN display. Paraffin cylinder (with the same dimensions of the DLM2) shifted 20 cm from the center of the scanned path \((x = 50 \text{ cm})\). The fit is not done because the signature shape is not complete.

Figure 5.5: HYDASCAN display. Paraffin cylinder (with the same dimensions of the DLM2) shifted 12 cm from the center of the scanned path \((x = 42 \text{ cm})\). In this case the fit is done because it was found a complete signature in the \(x\) range scanned and it is obtained a positive red status.
CHAPTER 5. RESULTS WITH THE PROTOTYPE HYDAD-D

5.4 Field tests

The field tests were performed using the motor-driven HYDAD-D set-up shown in Figs. 5.1 and 5.6. In order to evaluate the maximum depth at which the DLM2 could be detected the soil, a "flat" signature was systematically searched in the iThemba Labs ground fields. HYDASCAN is designed to give better results in a soil with homogeneous humidity distribution, therefore it is expected to see a flat signature or flat counts distributions in the detectors (like the shown in Figure 5.3) if the soil is homogeneous and there is no buried hydrogen-rich object. Due to the moisture inhomogeneities in the scanned soil, different responses were observed [20] (Figure 5.7). In Figs. 5.7.b and 5.8 for example, a clear signature appeared with no object buried, giving a "False Positive". Figure 5.8 shows how the amplitude of the signal is similar to the case of a DLM2 buried at 7 cm. Different places were scanned looking for a flat signature. From the total number of scanned places, 15% gave false positives [20]. If the moisture content is not homogeneous in the scanned path the counts far away from the center of this path (in 0 and 60 cm) could be different. See for example Figure 5.7.d. As we have seen, the number of counts is proportional to the amount of Hydrogen of the scanned material and therefore it can be said that the moisture content near the position 0 cm is slightly larger than the moisture content near the end of the scanned path (x = 60 cm). This is not seen in an homogeneous soil (e.g Figure 5.3). By looking at these possible differences the user has more tools to decide whether the signature that appears on the screen is due the presence of a buried object or due to the possible moisture inhomogeneities. Figure 5.9 shows the response of the HYDAD-D to DLM2 at different depths d (see Figure 5.1) in a soil with a non-uniform moisture distribution. Even in this case the DLM2 can be detected at d = 7 cm. Another location was found with smaller moisture inhomogeneities (Figure 5.10). In this case the DLM2 can be detected up to d = 12 cm with an acquisition time of 100 s.
Figure 5.7: HYDAD-D outputs at different places with no object buried. The counts distributions are not flat (a) c) and d)) and sometimes (b)) the difference amplitude is strong enough to give a false positive (red status without buried object).
Figure 5.8: HYDASCAN display: a) A true positive (DLM2 buried at $d = 7$ cm) and b) false positive (No object buried).
Figure 5.9: HYDASCAN display, DLM2 buried at different depths $d$ in an soil with non-uniform moisture distribution. (a) No object, (b) DLM2 at $d = 3$ cm and (c) $d = 7$ cm.
Figure 5.10: HYDASCAN display, DLM2 buried at different depths: $d =$ (a) 3.5 cm, (b) 5.8 cm, (c) 9 cm and (d) 12 cm.
5.4.1 The "Mine Field"

Figure 5.11: a) Side view of the HYDAD-D placed at the "Mine Field". b) DLM2 and plastic containers buried in the "Mine Field".

The "Mine Field" consists of several plastic containers (Figure 5.11b); some filled with water (150 ml) and others empty or filled with sand, which were buried at different depths in a grass field at iThemba Labs. It was created five months before the start of the experiments. The HYDAD-D was used in this "Mine Field" obtaining the results shown in Figs. 5.12 and 5.13. A negative (green) status is obtained in the place where there is no object buried and where the plastic container is empty (Figure 5.12b and 5.12c). As in the laboratory tests [20], no difference is seen when the buried object is rotated around an axis parallel to the soil surface (see Figs. 5.12d and 5.13a). The plastic container filled with water can be detected up to 20 cm depth (Figure 5.13d). An interesting result is obtained in the scan made in the place where the plastic container filled with sand was buried at 5 cm (Figure 5.13c). A clear signature and a high $P$ value are obtained showing that some Hydrogen anomaly is buried. This can be produced by the plastic of the container which has a high Hydrogen content itself. However the test made with the plastic container empty (Figure 5.12c) buried at 10 cm shows no signature. The Hydrogen content in the plastic container may be detected at 5 cm but not at 10 cm.

5.4.2 Hand held system tests

The hand-held system was used in the "Mine Field" and in the field used in section 5.4. The motor of the HYDAD-D was unmounted and the distance measurement device was connected to a hook attached to the detectors mounted in the hand-held device (Figure 5.14). All the measurements were done trying to maintain the same velocity than the motor-driven device. Figs. 5.15 and 5.16 show the results obtained at the "Mine Field" at two different positions,
CHAPTER 5. RESULTS WITH THE PROTOTYPE HYDAD-D

Figure 5.12: HYDAD-D outputs of the scans in the “Mine Field”. a) No object. b) plastic container filled with water buried at 5 cm c) plastic container empty buried at 10 cm and d) filled with water buried at 10 cm.

together with the previous scan outputs obtained with the motor-driven system. It is shown that the results (signature plots and \( P \) final value) are similar in the two cases. One advantage of using the motor-driven system is that the operator can stay further away of the neutron source and therefore the dose received will be less.

Finally the hand-held system was used to see the response of HYDAD-D to changes in the stand-off distance \( z \) (see Figure 5.1). The paraffin cylinder (with a radius of 4 cm and height of 3.5 cm, the same dimensions of the DLM2) was buried at 3 cm and different scans were made increasing the stand-off distance \( z \). Figure 5.17 shows the results obtained; the amplitude of the signal decrease with the height above the soil as was seen in the simulation (see Figure 4.7). Figure 5.17 shows also that the distance between the maxima of the counts distributions (pink and blue) decrease with \( z \). At a stand-off distance of 20 cm no signature is obtained because the distributions are overlapped, making the difference and therefore the signature function \( S(x) \) almost zero (Figure 5.17 d).
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Figure 5.13: HYDAD-D outputs of the scans in the “Mine Field”. Plastic container filled with water a) buried at 10 cm rotated 90°, b) buried at 15 cm, c) Plastic container filled with sand buried at 5 cm d) Plastic container filled with water buried at 20 cm.

Figure 5.14: HYDAD-D hand held system set-up.
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Figure 5.15: HYDASCAN outputs obtained using a) the motor-driven system and b) the hand-held system. The test object was a plastic container filled with water buried at 5 cm.

Figure 5.16: HYDAD-D outputs obtained using a): the motor-driven system and b) the hand-held system. The test object is the plastic container empty buried at 10 cm.
Figure 5.17: HYDAD-D outputs obtained with the paraffin cylinder buried at 3 cm, at different stand-off distances $z$ (height above the soil). $z =$ a) 5 cm, b) 10 cm, c) 15 cm and d) 20 cm.
CHAPTER 5. RESULTS WITH THE PROTOTYPE HYDAD-D
Chapter 6

Conclusions

• Experiments and Geant4 simulations of the neutron backscattering technique showed that the amplitude $D_0$ of the difference function (equation 4.2) decreases with the depth $d$ of the buried object and with the stand-off distance $z$ as expected (see geometry in Figure 4.1). Geant4 simulations show that at a stand-off distance of $z = 13$ cm a flat signal is obtained i.e the object is not detected (Figure 4.7). These simulations were done with a number of neutrons per $x$ position corresponding to $t = 2$ s of real exposition to the $^{252}$Cf neutron source. The maximum depth at which the DLM2 can be detected with this acquisition time is $d = 5$ cm (Figure 4.6).

• The implementation of NBT in the laboratory in this work showed that the dummy mine (DLM2) produces a signal from which it can be inferred its position up to a depth of $d = 15$ cm in dry sand with an acquisition time of 60 s per $x$ position (Figure 4.17).

• Including moisture in the soil where the hydrogen-rich object is buried produces an increment in the amplitude $D_0$ obtained with NBT, up to a maximum reached at a moisture of $\theta \approx 10\%$ (see Figure 4.23). At the same depth, the amplitude $D_0$ related to the number of thermal backscattered neutrons produced by the DLM2 presence increases both with the moisture content $\theta$ in the $0\% - 10\%$ range and with the amount of wet material around the DLM2 (see Figs 4.20, 4.21 and 4.22). This effect is interpreted as a pre-thermalization process where the moisture content helps the thermalization process to occur more efficiently in the hydrogen-rich object.

• Geant4 simulations reproduced the experimental results for the DLM2 placed at $d = 0$ cm, including moisture in the soil in the $\theta = 0\% - 10\%$ range (see Figure 4.23). At a moisture of $\theta = 42\%$ the simulated signal amplitude $D_0$ is too small compared with the amplitude obtained at the surface ($d = 0$ cm). This moisture content is the critical moisture value at which the DLM2 can not be detected because the number of thermal neutrons produced by the soil is about the same to the produced by the DLM2. At high homogeneous moisture values ($\theta > 42\%$), possible in other kind of soils [17], the simulation gives a negative signal which in principle can also be used for the detection in this cases (see Figure 4.12).
This work has shown the main characteristics of NBT implemented in laboratory conditions including tests with different moisture contents. The next step is to characterize the behaviour of NBT in Colombian soils including field tests with different hydrogen-rich objects and moisture contents. This will be possible by constructing a portable device.

### 6.1 HYDAD-D results

The HYDAD-D together with the software HYDASCAN, has been tested under field conditions at iThemba Labs grounds (Cape Town, South Africa). The DLM2 can be detected up to \( d = 12 \text{ cm} \) and the water container (150 ml) up to \( d = 20 \text{ cm} \) with a total acquisition time of 100 s in both cases. The 15\% of the scanned places with no test object buried, gave false positives \( (P_f > 6) \). This can be associated to moisture inhomogeneities in the scanned soil. The HYDASCAN graphical interface (see Figure 6.1) allows the user to see on-line, besides the signature function \( S(x) \), the counts distributions in each detector (blue and pink histograms) which can help to decide if the detected Hydrogen anomaly is due to a buried object or due to possible moisture inhomogeneities. The tests made with the hand-held system gave similar results to the motor-driven system ones. One advantage of using the motor-driven system is that the operator can stay further away of the neutron source and therefore the dose received will be less.
Appendix A

Simulation details

The Geant4 simulation tool-kit is widely used in fields such as nuclear physics, high energy physics and medical physics. In the present work several Geant4 classes were implemented to generate the simulation of the Neutron Backscattering Technique. This appendix describe the main details of the Geant4 simulation performed in the present work.

A.1 NBT set-up

One of the first steps in every simulation with Geant4 is the generation of the geometry and materials that are going to be considered. Figure shows the geometry implemented in the NBT simulation. It follows the experimental set-up shown in Figure 4.14. The wood box which contains the sand, a concrete column placed next to the wood box and a paraffin shielding where the $^{252}$Cf is kept in the laboratory, were also included. These three objects were included after the first simulations were found not able to achieve agreement with experimental results. One of the suggestions to obtain similar results was to include objects that could produce thermal neutrons as a background: the wood in the box that contains the sand, for example, is an organic material (hydrogen-rich) and therefore can help to the production of thermal neutrons that eventually could reach the detectors. As a first approximation to prove this suggestion, the definition given in [23] was used to define the material “Real Wood” in the simulation as wood (combination of Hydrogen, Carbon, Nitrogen and Oxygen) plus a certain value of residual moisture content (by weight):

```cpp
G4Material* Wood = new G4Material("Wood", density=0.5*g/cm3, ncomponents=4);
Wood->AddElement(H,fractionmass=0.06);
Wood->AddElement(C,fractionmass=0.5);
Wood->AddElement(O,fractionmass=0.42);
Wood->AddElement(N,fractionmass=0.02);
//The wood also have a residual moisture content between 10\% and 20\%
G4Material* RealWood = new G4Material("RealWood", density=1.2*g/cm3, ncomponents=2);
RealWood->AddMaterial(Wood, fractionmass=85*perCent);
RealWood->AddMaterial(water, fractionmass=15*perCent);
```

In this direction of using the experiment to validate the simulation results and using these last ones to understand in a better way the experiment, it was seen in the experimental results a
small but positive slope for the background (parameter $B_i$ in equation (4.1), see Figs. 4.6a and 4.16a). This could be explained by the presence of an hydrogen-rich material placed in the side of positive $x$. So it was included in the simulation set-up the concrete column and the paraffin shielding found in the experimental set-up (see Figure A.1) with the compositions given by the NIST and implemented in Geant4 in the form of predefined materials [9]:

```cpp
G4NistManager* man = G4NistManager::Instance();
G4Material* Concrete = man->FindOrBuildMaterial("G4_CONCRETE");
G4Material* Paraffine = man->FindOrBuildMaterial("G4_PARAFFIN");
```

On the other hand the detectors were included in the simulation following the characteristics of the LND detectors available in the laboratory (see Table 3.2). Their coverings made of stainless steel are also included. Once these materials and objects were implemented in the simulation geometry, the results were in a good agreement with the experimental ones (see Figure 4.16).

Figure A.1: NBT set-up implemented in the Geant4 simulation. It follows the experimental set-up shown in Figure 4.14. This plot is obtained with one of the visualization software that supports Geant4 geometries: DAWN.
A.2 The $^{252}$Cf neutron energy spectrum

As was mentioned in Section 3.3.1 the $^{252}$Cf neutron source has a specific neutron energy spectrum (see Figure 3.9). This spectrum was obtained with help of the Geant4 class called G4GeneralParticleSource in which the spectra and emission direction of the neutron source are specified through specific commands in the macro file:

```
/gps/ang/type iso
/gps/pos/type Point
/gps/particle neutron
/gps/pos/centre 0. 0. 36.0 cm
/gps/ene/type User
/gps/hist/type energy
/gps/hist/point 0.1 0.292815
/gps/hist/point 0.11 0.304753
...
```

These commands are read as: an isotropic point neutron source is located at $(0, 0, 36)$ cm. It follows an energy spectra defined by the user. The first argument in the command /gps/hist/point is the energy and the second number is the probability (non-normalized) a neutron has to be emitted with that energy. This distribution is chosen following the spontaneous fission spectrum (equation (3.14) and Figure 3.9).

A.3 Physics models

In the Geant4 simulation the user has to choose among several available physics models. They have to be chosen according with the type of particles and energy that are of interest. In particular for NBT, neutrons with energies from $0.025$ eV up to about $10$ MeV has to be taken into account. The high precision models (G4NeutronHP) offer data-driven models for neutrons with energies up to $20$ MeV. These models are based in the data found in the Evaluated Nuclear Data File [10]. The models included in the present work are:

- G4NeutronHPElastic
- G4NeutronHPInelastic
- G4NeutronHPCapture

The data files (cross sections and final states) in which these models are based on, are included in the package G4NDL3.11 which has data for all the elements used in the materials implemented in the NBT geometry (Fe, Cr and other elements found in the stainless steel of the detector coverings, $^3$He and Ar found in the detector gas, Si and O of the dry sand, etc). These high precision models can be used in the simulation of neutron interactions of fast neutrons down to thermal energies. At these low energies a special class is called to include effects of thermal motion of the target (G4NeutronHPThermalBoost), in which the target nuclei is considered not at rest in the laboratory frame but with certain initial velocity assigned according with the material temperature. In this case the incoming neutron can gain kinetic energy in the collision.
Figure A.2: Visual output of the simulated reaction $n + ^3\text{He} \rightarrow p + ^3\text{H}$ inside a cylindrical $^3\text{He}$ detector (see Figure 2.3). The green line represents the trajectory of the incident thermal neutron. The blue lines represent the trajectories of the proton ($p$) and the triton ($^3\text{He}$) produced in the reaction. The ionization electrons ($e^-$) produced by the proton and the triton inside the detector are represented in red.

Besides the neutron models, it has to be considered the interactions of the secondary particles produced by the neutron interactions. Neutron elastic scattering for example produces recoil nuclei (Si and O in the soil, $^3\text{He}$ and Ar in the detector gas, etc), the capture reaction inside the detector produces $p$ and $^3\text{H}$, etc. Physics models for these secondary particles are included in the NBT simulation. They are mainly:

- For generic ions (recoil nuclei):
  - G4MultipleScattering.
  - G4hLowEnergyIonisation.

- For electrons produced by the ionization process:
  - G4MultipleScattering.
  - G4LowEnergyIonisation
  - G4LowEnergyBremsstrahlung

- For $\gamma$-rays:
  - G4LowEnergyPhotoElectric.
  - G4LowEnergyCompton.
  - G4LowEnergyGammaConversion

The inclusion of these models necessary for the tracking of the secondary particles produced by neutron interactions, yields to a fairly complete description of the detection process inside the $^3\text{He}$ detectors (see Figs. A.2 and 3.10).
A.4 Multifunctional and sensitive detectors

Geant4 has two different kind of tools to extract information of interest from the tracking process of the particles through the defined geometry. With the class G4MultifunctionalDetector the user can define a detector to measure several quantities of interest at the same time. Each object of the class G4MultifunctionalDetector can have several scorers such as:

- G4PSTrackLength.
- G4PSDoseDeposit.
- G4PSFlatSurfaceCurrent.
- G4PSSphereSurfaceCurrent.
- G4PSFlatSurfaceFlux.

Each one of these scores measures a different quantity. It can be included also filters to take into account only certain particles of certain energy. For example, to measure the number of neutrons that went through the sand target and study by this the exponential attenuation of a neutron beam (Section 3.1.1), a multi-functional detector was defined with a G4PSFlatSurfaceCurrent scorer and a filter G4SDParticleWithEnergyFilter that only takes into account neutrons with a specific energy interval (eqs. (3.6) and (3.7)). The code for this implementation is:

```c++
// Create a new sensitive detector named "MyDetector"
G4MultiFunctionalDetector* detector = new G4MultiFunctionalDetector("MyDetector");
// Get pointer to detector manager
G4SDManager* manager = G4SDManager::GetSDMpointer();
// Register detector with manager
manager->AddNewDetector(detector);
// Attach detector to scoring volume (logic volume of the detector)
scoringVolume->SetSensitiveDetector(detector);
// Create a primitive Scorer named myScorer
G4PSFlatSurfaceCurrent* scorer = new G4PSFlatSurfaceCurrent("MyScorer",1);
// Create the filter
G4SDParticleWithEnergyFilter* filter = new G4SDParticleWithEnergyFilter("Neutron Filter");
// with only neutrons
filter->add("neutron");
// with energies in the interval:
G4double minEnergy = 0.9*MeV;
G4double maxEnergy = 1.1*MeV;
filter->SetKineticEnergy(minEnergy, maxEnergy);
// Attach filter to scorer
scorer->SetFilter(filter);
// Attach scorer to the MF detector
detector->RegisterPrimitive(scorer);
```

On the other hand if the user wants a controled way to extract data at each step it can be defined a G4SensitiveDetector. With this class and a G4VHit class, the user has access to information from each particle, in each simulation step, such as:
APPENDIX A. SIMULATION DETAILS

- Position.
- Kinetic energy (in the end of the step).
- Deposited energy (during the last step).
- Momentum (in the end of the step).
- Volume in which the particle is being tracked.

The cylindrical $^3$He-based detectors used in NBT (Section 3.3) were defined as sensitive detectors including in the G4VHit class the deposited energy. At each event the total deposited energy is accumulated and sent to a histogramming class to obtain the spectrum at each detector (see Figure 3.6).

A.4.1 Discriminating contributions in the detector

Including another quantities and information in the G4VHit class, we were able to discriminate which part of the spectrum was produced by different kind of particles and energies. Besides the deposited energy, it was included the name of the particle and the kinetic energy. When the histograming process was called, different histograms were saved with diferent deposited energies according with the particle that was taken into account in that particular step. This process were implemented to obtain the spectrum shown in Figure 3.10.
Appendix B

The HYDASCAN software

Figure B.1: HYDASCAN display for a scan over a DLM2 located at $x = 30$ cm. The explanation of the meaning of the parameters and plots on this display are given below.

The HYDASCAN software [22] is a program written in Visual Basic which analyzes the data that comes from the HYDAD-D electronics (Chapter 5). The following are some of the characteristics of the HYDASCAN display (Figure B.1):

- The top plot shows $A(x)$ (in pink), $B(x)$ (in blue) and the signature function $S(x) = D(x)/\sigma_D$ (in black). The red line is the plot of the function resulting from the fit to the function in equation (4.2).

- The bottom plot shows the value of the detection parameter $P$ as function of the total number of counts registered so far in the two detectors: $N = A + B$ whose value is shown in the Scan Statistics panel.

- The dark panel in the top of the display (traffic light panel) indicates the status of the scan according to the value of the detection parameter equation (5.4):
  - Negative ("Green") if $P < 3$.
  - Ambiguous ("Yellow") if $3 < P < 6$.
  - Positive ("Red") if $P > 6$.

- In the panel "Scan input From":
  The "List File" option is to load and analyze already saved files (off-line mode). The other two options are for the on-line mode.

- In the panel "Scan controls":
  "Auto-continue On" will read the list file in the off-line mode until it is finished. If it is deactivated the list file is read step by step by sequentially clicking on "Scan".

- If the "Auto-Halt On" option is activated, the measurement ends when one of the following conditions are fulfilled:
1. $N > N_{\text{min}}$ and $P > 6$.
2. $D_0 > 8$ and $P > 6$.
3. $N > N_{\text{min}}$ and $P < 3$ ($\times 5$ updates).
4. $N > N_{\text{max}}$.
5. List file exhausted.
6. Terminated by operator.

Where $N_{\text{min}}$ and $N_{\text{max}}$ are defined in the panel "File and Count Controls" see below.

- "Thread Alert On" will activate the sound alarm if the $P > 6$ and the scan is being done near to $x_0$: the possible position of the Hydrogen anomaly that results from the fit (Eq. 4.1).

- The panel "Scan Statistics" shows data that results from the scan:
  - First six are self-explanatory.
  - "P-final" shows the final (or current) value of the detection parameter.
  - "Signature" is a number that describes the shape of $S(x)$. (under development)
  - "Lines read" shows the number of data lines read from the list file.
  - "Position" shows $x_0$ (position of the object resulting from the fit), if an object has been detected.

- The panel "File and Count controls" shows:
  - The File header: Describes the path and the header of the file to be saved. The saved files have the name: "HDT$i$.dat" with $i$ the run number.
  - The run number is defined to label the scans made with the HYDAD-D. A run goes from the moment the scan begins (by clicking on "Scan") until the moment it finishes (Halt or Auto-Halt). The user decides to save or not the scan by changing the run number, putting a numerical label to the test by doing so, and clicking on "Save".
  - $N_{\text{upd}}$: # of lines of data required to be read (from the list file) between the updates of the display. In an "update" the bins of the histograms are filled with the data obtained since the last update and the corresponding fit is done again. The electronics is designed to accumulate the incoming counts of the detectors while an update is taking place.
  - $N_{\text{min}}$: is the minimum number of total counts required for an automatic halt.
  - $N_{\text{max}}$: is the maximum number of total counts that will be accepted in the scan.
  - $N_{\text{lines}}$: is the maximum number of lines of data to be read from the list file.
  - $S_{\text{fac}}$: Scale factor to $S(x)$. If $S(x)$ reaches values bigger than 9 is can be rescaled to fit in the plot with this factor.
  - $N_{\text{fac}}$: Scale factor to $N$. Changes the $N$ scale on the $P$ plot.
• The panel "Bin parameters" is not used except for the "Jsmoo" parameter. This panel was designed to control the calibration of the position measurement by Prof. Brooks. The parameter $J_{smoo}$ is the $m$ value described in Section 5.2.
Bibliography


