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A SIMULATION FOR DETECTING ANTI PERSONNEL LANDMINES WITH 14 MeV NEUTRON SOURCE

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MUHAMMED TEVFİK KAPLANOĞLU

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A Simulation for Detecting Anti Personnel Landmines

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Prof. Dr. Bülent GÖNÜL

by

Muhammed Tevfik KAPLANOĞLU

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Approval of the Graduate School of Natural and Applied Sciences

Prof. Dr. A.Necmeddin Yazıcı

Director

I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science

Prof. Dr. Ramazan Koç

Head of Department

This is to certify that we have read this thesis and that in our consensus/majority opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

Prof. Dr. Bülent GÖNÜL

Supervisor

Examining Committee Members	Signature
Prof. Dr. Bülent GÖNÜL	
Doç. Dr. Cumhur CANBAZOĞLU	
Doç. Dr. Ahmet BİNGÜL	

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Muhammed Tevfik KAPLANOĞLU

ABSTRACT

A SIMULATION FOR DETECTING ANTI PERSONNEL LANDMINES WITH 14 MeV NEUTRON SOURCE

KAPLANOĞLU, Muhammed Tevfik
M. Sc. in Engineering Physics
Supervisor : Prof. Dr. Bülent GÖNÜL
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The present thesis work investigates the problem of detecting anti personnel landmines with practically applicable neutron back scattering method and suggests a new simulation technique based on Monte Carlo method for the purpose of landmine detection using 14 MeV-neutron as the radiation source. Different landmine scenarios simulated for different explosives, soil types and buried depths have been considered within the framework of the present study. A set of electronic equipment including data acquisition and software systems to employ in APL detector system has been suggested to use it with the new technology having silicon photo multipliers. Along this line, the simulation software source code we developed has been inserted into the text. The results obtained are carefully discussed.

Key Words : Anti Personnel Landmine, Neutron back scattering, Characteristic gamma-ray, Radiation Simulation

ÖZET

14 MeV-NÖTRON KAYNAĞI İLE ANTİ PERSONEL KARA MAYINLARININ TESPİTİ İÇİN BİR SİMÜLASYON

KAPLANOĞLU, Muhammed Tevfik
Yüksek Lisans Tezi, Fizik Mühendisliği Bölümü
Tez Yöneticisi : Prof. Dr. Bülent GÖNÜL
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Bu çalışmada gömülü anti personel kara mayınlarının konumlarının belirlenmesi için nükleer fizik temelli uygulanılabilirliği yüksek nötron geri saçılım tekniği incelenerek Monte Carlo metodu tabanlı yeni bir simülasyon yaklaşımı geliştirilmiş ve simülasyonda 14 MeV enerjisine sahip nötronlar radyasyon kaynağı olarak kullanılmıştır. Çalışma; farklı patlayıcılar, farklı toprak tipleri ve farklı gömülme derinlikleri içeren geniş kapsamlı senaryolar dikkate alınarak yürütülmüştür. Çalışma sonuçları doğrultusunda, ilgilenilen konu çerçevesinde, yeni bir teknoloji olan silikon foto çoğaltıcılar kullanılmak üzere ilgili veri toplama sistemleri ve yazılımlarını da içeren yeni bir elektronik set önerisinde bulunulmuştur. Geliştirilen simülasyon yazılımının kaynak kodu metin içine eklenmiştir. Bulunan sonuçlar dikkatlice tartışılmıştır.

Anahtar Kelimeler : Anti Personel Mayınları, Nötron geri saçılımı, Karakteristik Gama Işını, Radyasyon Simülasyonu

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CHAPTER-1

INTRODUCTION

Detection of anti personnel landmines (APL) is a common problem for many territories because of the mine sizes and used materials inside it. It makes difficult to detect small sized landmines with conventional techniques such as detection using metal detectors and natural sniffers. Additionally; buried depths, environmental conditions and mine clearance purpose also can make the problem as a challenge. APL's are developed for blocking an area or path for civilian or military usage. This type of mines often used in terrorist attacks and civilian wars even in public areas especially in Middle East countries.

At the mine clearance operation side, two purposes occur:

- Detection, bypass or breach for military purposes (Passing the mine field as possible as fast).
- Mine clearance a field for civilian purposes (Clearing whole area for public usage).

Both purposes need a sensitive detection technology and secure mine clearance method. There are several methods except nuclear techniques for landmine detection[1]. In nuclear techniques two methods generally used are significantly considered. These are neutron back scattering and neutron induced gamma rays which are the main topics of the present thesis work. In these methods, a radioactive material/source emits radiation to the target and detector system counts and measure energy levels of back scattered neutrons and gamma rays. Environmental conditions such as humidity, distance, soil type can affect efficiency of method.

These methods are not new for APL detection and used many industrial areas. However developed nuclear APL detector systems are still in prototype phase and not widely used in the world. Emerging semiconductor and computing technologies can contribute to developing new APL detectors with mixture detection methods.

Simulation is the first approach to development of a new detector system. Due to this reason, a modular simulation software has been developed during our study using Geant4[2] and Root[3] toolkit/softwares. They have ability to simulate radioactive source, geometry, solid type and gives outputs as histogram, 3D, 2D, etc plots.

These two toolkits have ability to simulate and analyze radiation transportation for particle, nuclear, plasma physics. In this thesis, following capabilities used for back scattered neutron and gamma detection scenario on selected explosives. We follow a framework:

- Defining a scene for different types of geometries and materials with possibility of quick changes.
- Using radioactive sources with its energy and angular spectrum.
- Simulating selected physical interactions of radioactive particle with user defined target material.
- Analysing particle data (energy, direction, dose) in anywhere of the scene.
- Creating optical photons to define compatible detector system.

A simulation result of course can not completely cover all conditions for an expected scenario but it aim to understand the behavior of the operation for developing a detector system or suggesting a novel detection system. There are several radiation detector systems used for neutron counting and gamma spectrum analysis, but a new technology would make possible to detect the radiation more precisely, which is called as silicon photo multiplier(SiPM).

SiPMs are new technologies for detecting relatively small photon lights for a certain wavelengths within electromagnetic spectrum. SIPMs have a detection ability of even a single photon the corresponding efficiency, which is called as single photon detection efficiency, is generally about ~%50 for an average SIPM. A single SIPM consist of many photo diodes which are to be rushed in a small area (in general thousands of photo diodes that are paralelly inserted into 1x1 to 6x6 mm area). It is stressed that SIPM's are particularly developed for detection of light signals not for detection of a radioactive particles directly, because of this reason a scintillator material should be coupled with a SIPM.

A detector system with scintillators can suggested be in order to use in neutron back scattering method to search a soil area as an image. Approximations used to develop the system mentioned above have discussed through the final chapter.

In Chapter 2, a general overview involving theoretical background on the related topic has been given, together with the models used in such detections. Chapter 3 includes discussions on detecting neutrons based on nuclear reactions with proper simulations. In Chapter 4, we have proposed a novel detector system for detecting anti personnel landmines with necessary electronic device and software. Chapter 5 gives a summary on the whole work carried out in this.

CHAPTER-2

THEORETICAL BACKGROUND AND MODELS

2.1 Anti Personnel Landmines

APLs are designed and developed to injure/block personnel activities in buried area or path, its explosion triggers when a victim interact with its surface, it is also possible to activate an APL using a remote control. Setting up an APL is a simple process but cleaning is not, non cleaned APL territory makes impossible to remain civilian life in APL area. A cost effective and humanitarian methods still is need to clean APL areas. APLs are generally shaped in form of a disk or cylinder with diameters from 20 to 125 mm, length from 50 to 110 mm[4]. Generally used explosive materials called as TNT, Tetryl and Comp B. It is buried usually close to ground surface, because deep buried APL can be deactive of harmless. Even APL near to surface rarely, may go deeper in time.

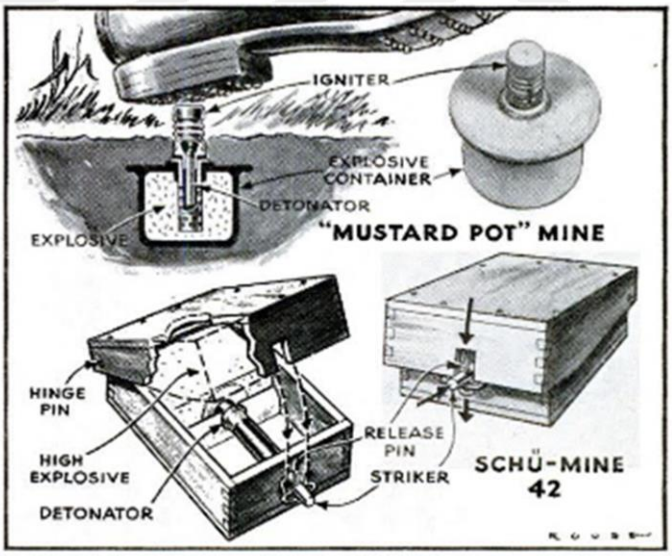

Figure 2.1 General working procedure of an anti personnel landmine.

APL explosion's effect is based on the used explosive material, buried depth and APL size. It can injure a part of body or kill personnel who step on. It is also possible to active an APL remotely with a signal, some handmade explosives use this principle for hiding landmine.

2.2 ENVIRONMENTAL CONDITIONS

Most of the detection difficulty comes from environmental conditions, APL can be under a grass, snow or a runlet. This conditions creates noisy signals for detector systems. Different detection methods have its own advantages and disadvantages; for example, weather critically effect due to humidity ratio in the air, buried depth can be block neutron particle to interact with APL surface or the explosive material inside it. Another challenge is detection distance of the detector for catching emitted signals.

Simulating full environmental conditions are indeed not completely possible, however its possible to simulate most known environmental conditions with computation technology of today. The assumed that environmental conditions are listed below.

- Soil types and air conditions.
- Explosive materials used in the landmine.
- Buried depth of the landmine.
- Detection distance from surface to detector.

2.2.1 Soil Types

In advance of the detailed research of soil compositions, it is assumed that there are a few dominant components which can easily find the chemical ingredients of it for use in Geant4 code. But there are many types of soils and classifying these soils is more related to organic chemistry. In the minefield, the APL were placed in randomly distributed area and every location can has its own soil type. From a general aspect, an averaged elemental composition of a soil sample can be found from pH ratio of it and the pH value of a soil which can be found on soil databases easily. However, for a better estimation of a specific soil, the percentages of main components of soil (clay, silt and sand) should be used.

The Harmonized World Soil Database (HWSD) [5] provides information on the soil composition for different locations on world map. Over 16000 different locations are recognized in the HWSD. The database shows the composition of each soil and standard soil parameters for topsoil (0-30 cm) and subsoil (30-100 cm). Database provides chemical and physical soil properties for topsoil and subsoil separately. In this study, the HWSD database has been added to Geant4 toolkit for the calculation of soil contents for user specified locations from percentage information of three dominant structures; Clay, Silt and Sand. Soil consist of many different types of materials, when soil divides general parts, soil types can be define using clay, sand and silt ratios. Chemical formulas for clay, sand and silt are Al2O3-2 SiO2-2H2O, SiO2, SiO2-KAlSi3O8-NaAlSi3O8-CaAl2Si2O8. Our code used in the present work will employ the standard compositions of this three dominant structures to make an approximate estimation of the soil composition in specified locations.

2.2.2 Explosive Materials

Explosives are reactive substance which contains high amount of energy as its potential to explode. In APL, the APL reaction can be triggered due to light, heat, pressure or mixing another material inside the landmine. APL has variety forms of explosive material compositions but most of the common explosive materials are combinations of Hydrogen, Nitrogen, Oxygen and Carbon. The materials can show distinguishing properties for detecting explosive but the air already contains oxygen, nitrogen and hydrogen (based on humidity ratio). Oxygen, Hydrogen based on humidity, also organic carbon can be found inside soil as well.

Table 2.1 Explosive materials and chemical compounds.

Name	Formula	H (%)	N (%)	O (%)	C (%)
Ammonium nitrate (AN)	H4N2O3	5.037	34.997	59.9652	-
Ammonium picrate (Expl D)	C6H6N4O7	2.457	22.762	45.501	29.2784
Cyclonite (RDX)	C3H6N6O6	2.722	37.836	43.219	16.2222
Ethylenediamine dinitrate	C2H10N4O6	5.415	30.101	51.576	12.9061
Guanidine nitrate	CH6N4O3	4.953	45.892	39.315	9.8381
Hexamethylenetriperoxide diamine	C6H12N2O6	5.81	13.457	46.114	34.6181
Hexanitrohexaazaisowurtzitane	C6H6N12O1	1.38	38.358	43.815	16.4461
Hydrazine nitrate	H5N3O3	5.301	44.204	50.493	-
Mannitol hexanitrate	C6H8N6O18	1.783	18.586	63.692	15.937
Monomethylamine nitrate	CH4N2O3	4.379	30.431	52.141	13.047
Nitrocellulose	C6H7N3O11	2.374	14.141	59.23	24.253
Nitroglycerin (NG)	C3H5N3O9	2.219	18.504	63.409	15.867
Nitrotriazolone (NTO)	C2H2N4O3	1.549	43.076	36.904	18.469
Octogen (HMX)	C4H8N8O8	2.722	37.836	43.219	16.222
Pentaerythritol tetranitrate	C5H8N4O12	2.55	17.722	60.731	18.996
Picric acid	C6H3N3O7	1.319	18.341	48.884	31.454
Tetrazene	C2H8N10O	4.285	74.443	8.503	12.767
Tetryl	C7H5N5O8	1.755	24.389	44.575	29.279
Trinitrobenzene (TNB)	C6H3N3O6	1.418	19.718	45.046	33.816
Trinitrotoluene (TNT)	C7H5N3O6	2.218	18.5	42.264	37.016
Triaminoguanidine nitrate	CH9N7O3	5.427	58.666	28.719	7.186
Triaminotrinitrobenzene	C6H6N6O6	2.342	32.555	37.186	27.915
Trinitroazetidine (TNAZ)	C3H4N4O6	2.098	29.167	49.975	18.758
Trinitropyridine	C5H2N4O6	0.941	26.169	44.838	28.05
Urea nitrate	CH5N3O4	4.095	34.143	52.001	9.759

The most known explosives and their material compositions is listed above, dominant materials inside the explosives are nitrogen and oxygen which are also highly available in air. So, for detecting explosives it is important to describe material differences between the air, soil and explosive.

Our code has ability to create all these types of explosives through the simulation, some explosive materials such as purified Uranium is sensitive to neutron and a neutron access to a neutron sensitive explosive can cause serious effects however there is no known nuclear APLs yet and a neutron based detection system can be used for these generic explosive materials.

2.3 General Methods for Landmine Detection

There are several methods to detect anti personnel landmines. It is possible to expand the methods used with different variants and mix systems, the general list below explains briefly the main methods for detection approximation:

- **Sight :** The most basic method is the sight, it is difficult to see APL directly event on the surface. But when it is sighted, it can be triggered by an educated person or disassembly for preventing an explosion. A camera system can be used to detect with limited efficiency via scanning soil surface with an automated system.

- **Hand Clearance :** This method based on take out of landmine from soil, soil should be digged out by an expert carefully. It can be applied for only detected (generally by sight) APL. It is now more effective to use remote controlled APL's.

- **Mechanical Clearing :** This method aims at directly making APL's burst. A well shielded vehicle enter into mine field and crush landmines. This method is a brute force and quick way for military operations however not sensitive for clearing an area for public access.

- **Thermal Imaging :** Advanced imaging techniques can detect sudden thermal changes on APL, soil and APL has different heat transfer ratios and when a thermal change occur in weather or soil, it is possible to detect position of the APL. Its useful for dry areas but not useful in snowcapped fields.

- **Plants :** This method is based on using explosive sensitive (like as TNT) plants but for not explored landmines. Explosive sensitive plants' behaivour changes when it reach to explosive (Changing color, growing up and other signs).

- **Natural Sniffers :** Using educated dogs or other smell sensitive animals for finding the place of APL's are alternative ways. These are widely used in through the world but the efficiency of the method is limited with animal capabilities.

- **Antibodies :** It is one of effective methods for special targeted explosive materials. This is based on producing explosive sensitive material and spreading the material on to minefield.

- **Forced Reaction (Laser) :** Detected APL can be triggered by a laser pulse for explosion or makefield scanned by a laser system. This method is based on the scanning of the whole area with the intense laser system. It is effective for joining an area for military purposes but not effective for a complete detection or cleaning area.

- **Impulse Radar or Microwave :** This is based on the measuring resonance frequencies of the ground by scanning an area. It makes possible to detect the size and material of APL remotely. The system is one of highly successful method to mapping on surface with its underground materials to detect APL points. A wave emitter scans area, after receiving signals, a clearing method (based on area) can be used for demining.

2.4 Previous Works for Nuclear Methods

Like other methods, there are several research as for Neutron Backscattering and Neutron Induced Gamma measurements. Different type detector systems used as detector for such research. Some of most known Neutron Backscattering method based detectors are listed below:

- **Delft University Neutron Backscattering Landmine Detector (DUNBLAD)**[6]

  It is a portable and ergonomic landmine detector which combines both electromagnetic induction and neutron backscattering method to detect APL, for which Cf-252 source has been used as radioactive source and it warns the user when detect a hydrogen-rich anomaly on the scanning ground. The purpose of the detector system is to detect both mechanic and plastic APL together. They're using 3He filled detectors to detect low energy backscattered neutrons.

Figure 2.2 Dunblad detector prototype testing.

- **ESpecial CAr for LAndmine DEtection (ESCALADE)**[7]

  ESCALADE is a mountable detector system which is consist of both radio frequency and neutron detection methods together. The detector system mainly use GPR and magnetic gradiometer techniques to detect land mines. They have also ability to use NBS technique.

Figure 2.3 ESCALADE Detector prototype testing.

- **HYdrogen Density Anomaly Detector (HYDAD)** [8]

HYDAD is a device that designed and developed to detection of hydrogen rich materials inside the soil. The system consist of a neutron source for fast neutrons and two identical slow neutron 3He detectors.

Figure 2.4 HYDAD Detector prototype testing.

2.5 Needed Detector System to Overcome Known Issues

The detector systems which listed in the previous section, work with the following principles:

- Using Cf252 as radioactive source.
- Scanning the area by a person or a car.
- Using 3He based neutron detectors.

All the systems have its own advantages and disadvantages. In our suggestion, through Chapter 4, we show that it is possible to develop lightweight and SIPM based detection system to detect landmines with neutron generators. It should work with modular principles to mount a drone or any other detection system like metal detectors or RF based detectors.

CHAPTER-3

NEUTRON INTERACTIONS WITH MATTER AND THE SIMULATION

3.1 Neutron Particle

Neutron is a subatomic particle with a mass of 939.5 MeV/c^2, which has a form of ionizing radiation and have a potential to defect interacting material. Neutrons have a velocity range between 100 to 1000 m/s **[**9**].** They have a mass but no electrical charge. Due to its non-electrical characteristic it has quite low interaction ability with electric field, which embarrass detecting neutrons directly. It is several interactions with target materials are based on its cross section and energy.

In general, a neutron can be described with its mass, velocity and wavelength or the corresponding wave number.

3.2 Neutron Interactions with Matter

Neutrons are neutral particles, they've no positive or negative charge and travel in straight lines, for deviating a neutron's path it should interact with a nucleus. After interaction with a nucleus its direction and energy can be changed. Electrons around the nucleus or electric field does not effect neutron's momentum.

Neutron interactions can be classified as

- Scattering
  - Elastic Scattering (Energy conserved (n,n'))
  - Inelastic Scattering (Energy lost due to interaction (n,n', γ)
- Absorption
  - Gamma Emission with Neutron Absorption
  - Proton Emission with Neutron Absorption
- Fission

Neutron electron interactions are negligibly small from measurable point of view, hence neutron interacts with nucleus and during the interaction the following steps are performed between neutron and nuclei.

- **Entering to nuclei :**
  Incoming neutrons interact with target nuclei and give an excitation to nuclei, which appears in the binding energy.

- **Keeping in nuclei :**
  After entering, nuclei hold the neutrons and create new nuclear bonds to become as a new isotope. Along this step there are two possibilities to initiate: terminating the neutron inside the nuclei (which is called absorption), and scattering (scattering with neutrons with their original energies or inelastic scattering with a gamma ray) or fission (emitting more than one neutron due to unstable nuclei).

- **Emitting Particles :**
  After holding neutron in nuclei, the target matter can emit neutron, gamma or proton.

Elastic scattering is similar like collision between two billiard balls, kinetic energy loss for per interaction based on incoming particle mass and speed. In inelastic scattering, neutron has sufficient kinetic energy to push the target atom to excited state, excited atom decays (emits γ and neutron) to its ground state. In this process neutron continues with a lower energy and γ ray energy is based on target matter type, which is also called as characteristic γ energy. The absorption processes are also similar with just one difference: in the absorption, the nuclei does not emits neutron. To understand the relation between neutron particles and target (explosive and soil) we need to understand the cross sections between them. The dominant materials inside the general explosives are O,C,H,N and for soil the materials are Al, O, Si, H, K, Na, Ca.

Shared materials for both soil and explosive are: Oxygen, Carbon, Hydrogen. Oxygen and nitrogen also avaible in air with different percentage ratios, so detecting oxygen or nitrogen can not give a significant information about the things under the soil. Carbon ratio is also not homogen for soil and explosive. But hydrogen ratio change on a detector system can give an information for buried material.

To understand the interactions, Hydrogen and Carbon cross sections quoted in ENDF [10] database give the following information for neutron cross sections of the materials.

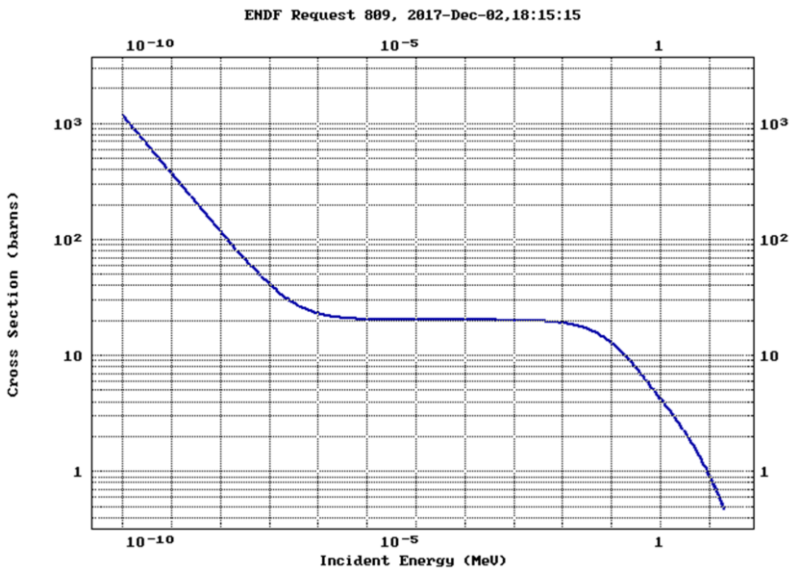

Figure 3.1 Neutron cross section for H-1 (ENDF/B-VII.1)

In the Figure 5 the most possible interactions between neutron and H-1 are at below than 10^{-5} MeV but this energy can not be sufficient to reach APL under soil.

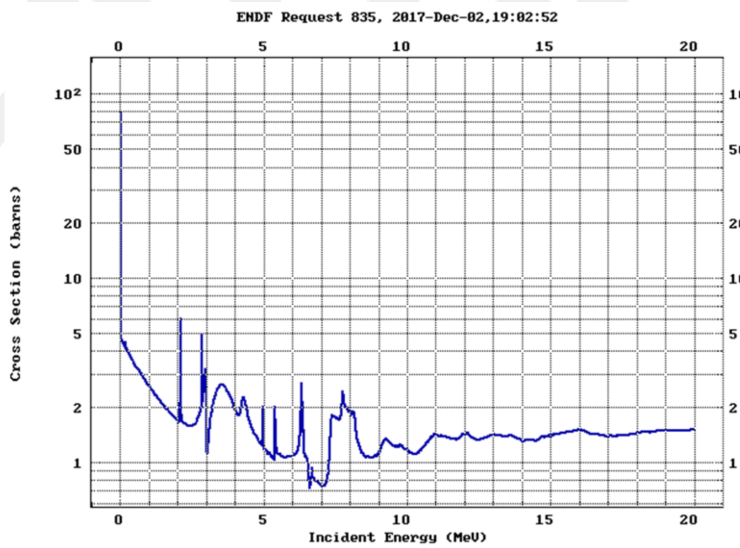

Figure 3.2 Neutron cross section for C-12 (ENDF/B-VII.1)

The Figure 3.1 and 3.2 show that, hydrogen has more cros section below 1 MeV neutrons while the total cross sections in C-12 case below 14 MeV are approximately close each other.

3.3 Neutron Sources

Neutrons can be produced with radioactive neutron sources or reactions which are created by a charged particle. For neutron generation process, most used reactions are listed below:

1. $\gamma + {}^{9}Be \rightarrow 2\,{}^{4}He + n - 1.67$ MeV
2. $^{9}Be + \alpha \rightarrow {}^{12}C + n + 5.91$ MeV
3. $^{2}H + {}^{2}H \rightarrow {}^{3}He + n + 3.29$ MeV (neutron energy about 2.4 MeV)
4. $^{3}H + {}^{2}H \rightarrow {}^{4}He + n + 17.6$ MeV (neutron energy about 14.1 MeV)
5. $^{3}H + {}^{1}H \rightarrow {}^{3}He + n - 0.763$ MeV

For neutron generators, reaction (3) and (4) are mostly used ones and easy to find these type of generators in world-wide. Neutron generators can be used to create a reaction in target material, high energy neutron can go deeper than the lower energy neutrons due its energy.

Table 3.1 General Reaction for Producing Neutrons[11]

Reaction	**Neutron Energy (MeV)**
$^{3}H(d,n)^{3}He$	2.448
$^{3}H(p,n)^{3}He$	0.0639
$^{3}H(d,n)^{4}He$	14.064
$^{9}Be(\alpha,n)^{12}C$	5.266
$^{12}C(d,n)^{13}N$	0.0034
$^{13}C(\alpha,n)^{16}O$	2.07
$^{7}Li(p,n)^{7}Be$	0.0299

3.4 Monte Carlo Simulation

Monte Carlo method is a numerical approximation based on random numbers. The method is one of the most used simulation technique for radiation transport calculations. General working principle of the method for radiation transport is solving statistical possibilities for reactions between incoming particle and the target using seeded random numbers for possible reactions. Creating a radiation transport code from scratch is not necessary, the easiest and most trustable way is adding a scenario in to previously generated toolkits. We have used Geant4 toolkit from CERN to run the simulation.

For the anti personnel landmine simulation, two types of approximations are applied:

1-Test simulation to check the code and the scenario.
2-Full simulation with real explosive.

For the back scattered neutrons and gamma rays detected with a perfect detector. Purpose of the simulation is to determine possible reactions and observing back scattered gamma and neutron particles to understand possibility of detecting anti personnel landmine.

The following code blocks inserted in to Geant4 for initiating the simulation.

3.4.1 Detector Construction

The following code creates soil, explosive and the detectors; it is possible to play with the materials inside the soil and explosive, soil depth, explosive depth, and the detector altitude.

...

```
     G4VPhysicalVolume* DetectorConstruction::Construct()
     {
         // Construct materials
         ConstructMaterials();

         G4bool checkOverlaps = true;
         /* World Dimension which will be divided by two
*/
         WorldH_X = 1*m;
         WorldH_Y = 1*m;
         WorldH_Z = 1*m;
         MWorld = G4Material::GetMaterial("G4_Galactic");
// World materials

         /* Creating World */
         SWorld =
new G4Box("SWorld", WorldH_X, WorldH_Y, WorldH_Z);

         LWorld =
new G4LogicalVolume(SWorld, MWorld, "LWorld");

         PWorld =
new G4PVPlacement(0, G4ThreeVector(), LWorld,
                               "worldPhysical", 0, false,
0, checkOverlaps);

         G4Material*              Al                 =
G4Material::GetMaterial("G4_Al");

         G4Material*              Si                 =
G4Material::GetMaterial("G4_Si");

         G4Material*         O                       =
G4Material::GetMaterial("G4_O");

         G4Material*         H                       =
G4Material::GetMaterial("G4_H");

         G4Material*         K                       =
G4Material::GetMaterial("G4_K");
```

```
        G4Material*                 Na                 =
G4Material::GetMaterial("G4_Na");

        G4Material*                 Ca                 =
G4Material::GetMaterial("G4_C");

        G4Material* N = G4Material::GetMaterial("G4_N");

        // Creating Clay
        G4double DensityClay = 1250*kg/m3;
        G4Material*  Clay  =  new  G4Material("Clay",
DensityClay, 4);

        Clay->AddMaterial(Al, 20.9029*perCent);
        Clay->AddMaterial(O, 55.7772*perCent);
        Clay->AddMaterial(Si, 21.7582*perCent);
        Clay->AddMaterial(H, 1.5617*perCent);

        // Creating Sand
        G4double DensitySand = 1520*kg/m3;
        G4Material*  Sand  =  new  G4Material("Sand",
DensitySand, 2);

        Sand->AddMaterial(Si, 46.7435*perCent);
        Sand->AddMaterial(O, 53.2565*perCent);

        // Creating Silt
        G4double DensitySilt = 2.798*g/cm3;
        G4Material*  Silt  =  new  G4Material("Silt",
DensitySilt, 6);

        Silt->AddMaterial(Si, 28.7615*perCent);
        Silt->AddMaterial(O, 47.3330*perCent);
        Silt->AddMaterial(K, 4.4488*perCent);
        Silt->AddMaterial(Al, 12.2804*perCent);
        Silt->AddMaterial(Na, 2.6159*perCent);
        Silt->AddMaterial(Ca, 4.5603*perCent);

        G4double PercentageClay = 23;
        G4double PercentageSand = 40;
        G4double PercentageSilt = 23;
        G4double DensitySoil = 1.39*g/cm3;

        // Mixing Soild
        MSoil = new G4Material("Soil", DensitySoil, 3);
        MSoil->AddMaterial(Clay,
PercentageClay*perCent);
        MSoil->AddMaterial(Sand,
PercentageSand*perCent);
```

```
        MSoil->AddMaterial(Silt, 
PercentageSilt*perCent);

        // MSoil = G4Material::GetMaterial("G4_H");

        /*Filling World with Soil*/
        SoilDepth = 25*cm;

        soil_position = -(WorldH_Z)+SoilDepth/2;

        SSoil =
new G4Box("SSoil", WorldH_X, WorldH_Y, SoilDepth/2);

        LSoil =
new G4LogicalVolume(SSoil, MSoil, "LSoil");


new G4PVPlacement(0, G4ThreeVector(0, 0, soil_position), 
LSoil,
                              "PSoil", LWorld, false, 
0, checkOverlaps);

        G4double explosive_active=1;
        if(explosive_active){

        // Creating Explosive Material.
        explosive_density = 1.65*g/cm3;
        H_Percentage = 5.810*perCent;
        O_Percentage = 46.114*perCent;
        N_Percentage = 13.457*perCent;
        C_Percentage = 34.6181*perCent;

        explosiveMaterial = new G4Material("Explosive", 
explosive_density, 4);

        explosiveMaterial->
    AddMaterial(H, H_Percentage);

        explosiveMaterial->
    AddMaterial(O, O_Percentage);

        explosiveMaterial->
    AddMaterial(N, N_Percentage);

        explosiveMaterial->
    ddMaterial(Ca, C_Percentage);

        explosiveSize = 5*cm;
        explosiveZ    = 1*cm;
```

```
         explosive_depth = 0*cm;
         explosive_position       =       +(SoilDepth/2)-
(explosiveZ/2)-explosive_depth;

         explosive_Solid =
new     G4Box("Explosive     Solid",     explosiveSize/2,
explosiveSize/2, explosiveZ/2);

         explosiveLogical =
new  G4LogicalVolume(explosive_Solid,  explosiveMaterial,
"Logical Explosive");

new                                       G4PVPlacement(0,
G4ThreeVector(0,0,explosive_position), explosiveLogical,
                           "Explosive", LSoil, false, 0,
checkOverlaps );

         }

         detector_thickness = 1*cm;
         detector_position  = 10*cm;

         detector_material                               =
G4Material::GetMaterial("G4_AIR");

         detector_solid =
new    G4Box("Detector    Solid",    WorldH_X,    WorldH_Y,
detector_thickness/2);

         detector_logical =
new   G4LogicalVolume(detector_solid,   detector_material,
"Detector Logical");

         new
G4PVPlacement(0,G4ThreeVector(0,0,detector_position),
detector_logical,"Detector",      Lworld,       false,0,
checkOverlaps);

         return PWorld;
     }
 …
```

3.4.2 Particle Generator

For particle (neutron) source, the following code is inserted into Geant4, it simulates a neutron source and give a direction to that source.

…

```
# 1D accelerator beam
/gps/particle neutron
/gps/pos/type Beam
#
# the incident surface is in the y-z plane
/gps/pos/rot1 1 0 0
/gps/pos/rot2 0 1 0
#
# the beam spot is centered at the origin and is
# of 1d gaussian shape with a 3mm central plateau
/gps/pos/shape Circle
/gps/pos/centre 0. 0. 0. mm
/gps/pos/radius 25. mm
/gps/pos/sigma_r .2 mm

# the beam is traveling along the x-axis with 2 degrees
dispersion
/gps/ang/rot1 1 0 0
/gps/ang/rot2 0 1 0
/gps/ang/type beam1d
/gps/ang/sigma_r 2. deg
#
/gps/ene/type Gauss
/gps/ene/mono 14 MeV
/gps/ene/sigma 10. keV
```

…

3.4.3 Data Scoring

To score the information, the following code is prepared.

```
...
preStepPoint = tStep->GetPreStepPoint();
postStepPoint= tStep->GetPostStepPoint();

  if(
        postStepPoint->GetStepStatus() == fGeomBoundary
        &&
        tStep->IsLastStepInVolume()
        &&
        preStepPoint->GetPhysicalVolume()->GetName() == "worldPhysical"
        &&
        postStepPoint->GetPhysicalVolume()->GetName() == "PSoil"
        &&
        tStep->GetTrack()->GetDynamicParticle()->
GetParticleDefinition()->GetParticleName() == "neutron"
    ){
    histoManager->FillHisto(0, postStepPoint->GetKineticEnergy()/MeV,1);
  }

  if(
        postStepPoint->GetStepStatus() == fGeomBoundary
        &&
        preStepPoint->GetPhysicalVolume()->GetName() == "PSoil"
        &&
        postStepPoint->GetPhysicalVolume()->GetName() == "Explosive"
        &&
        tStep->GetTrack()->GetDynamicParticle()->
GetParticleDefinition()->GetParticleName() == "neutron"
    ){
    histoManager->FillHisto(1, postStepPoint->GetKineticEnergy()/MeV,1);
  }

  if(
        postStepPoint->GetStepStatus() == fGeomBoundary
        &&
        preStepPoint->GetPhysicalVolume()->GetName() == "worldPhysical"
        &&
        postStepPoint->GetPhysicalVolume()->GetName() == "Detector"
        &&
        tStep->GetTrack()->GetDynamicParticle()->
GetParticleDefinition()->GetParticleName() == "neutron"
    ){
     histoManager->FillHisto(2, preStepPoint->GetKineticEnergy()/MeV,1);
  }

  if(
        postStepPoint->GetStepStatus() == fGeomBoundary
        &&
```

```
        preStepPoint->GetPhysicalVolume()->GetName() == "worldPhysical"
        &&
        postStepPoint->GetPhysicalVolume()->GetName() == "Detector"
        &&
        tStep->GetTrack()->GetDynamicParticle()->GetParticleDefinition()-
>GetParticleName() == "gamma"
    ){
    histoManager->FillHisto(3, preStepPoint->GetKineticEnergy()/MeV,1);
  }
...
```

3.5 Test Simulation

Before the full simulation, the detection ability is tested with the SiO type soil and 5x5x1 cm^3 Hydrogen cube through different depths. 14 MeV Neutron Generator is used as particle source from 10 cm distance. We have observed that the source to the surface approximately %80 of the neutrons are reached.

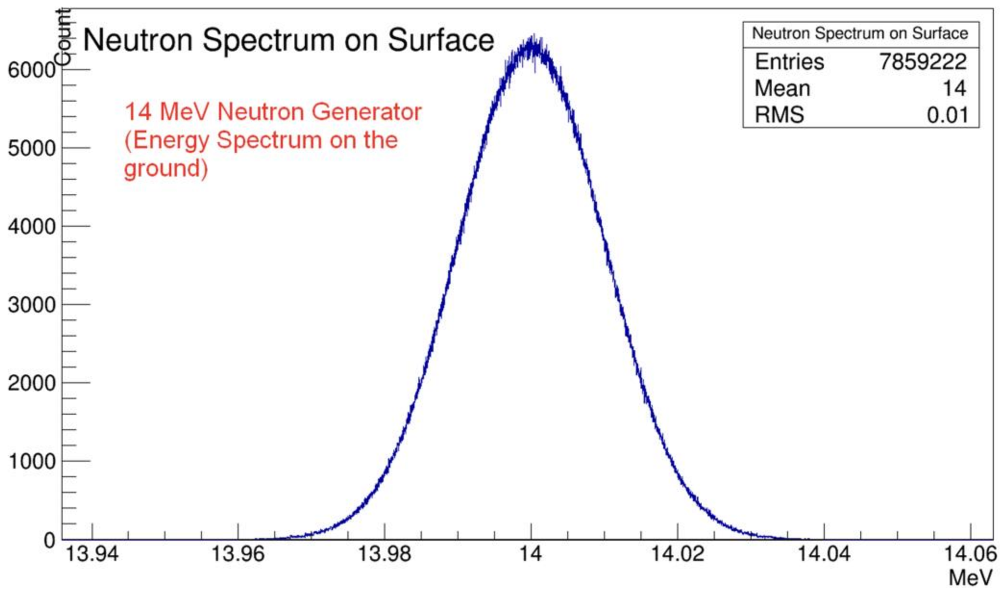

Figure 3.3 Neutron energy spectrum on the soil surface.

For the neutron generation, GPS (General Particle Source) Code is used inside Geant4. The commercially available neutron sources have a capacity up to 1x10^8 n/s with 14 MeV (or 2.5 MeV), and the generated neutron in the simulation is 1x10^ 7 neutrons, it corresponds 0.1 seconds of the real neutron generator flux.

Following parameters are observed in the all simulations :

- Neutron energy spectrum on the soil surface.
- Neutron energy spectrum on the explosive surface.
- Neutron energy spectrum on the detector. (Also counts)
- Gamma energy spectrum on the detector.

A perfect detector is assumed as a plate to understand the full behaviour of the incoming particles.

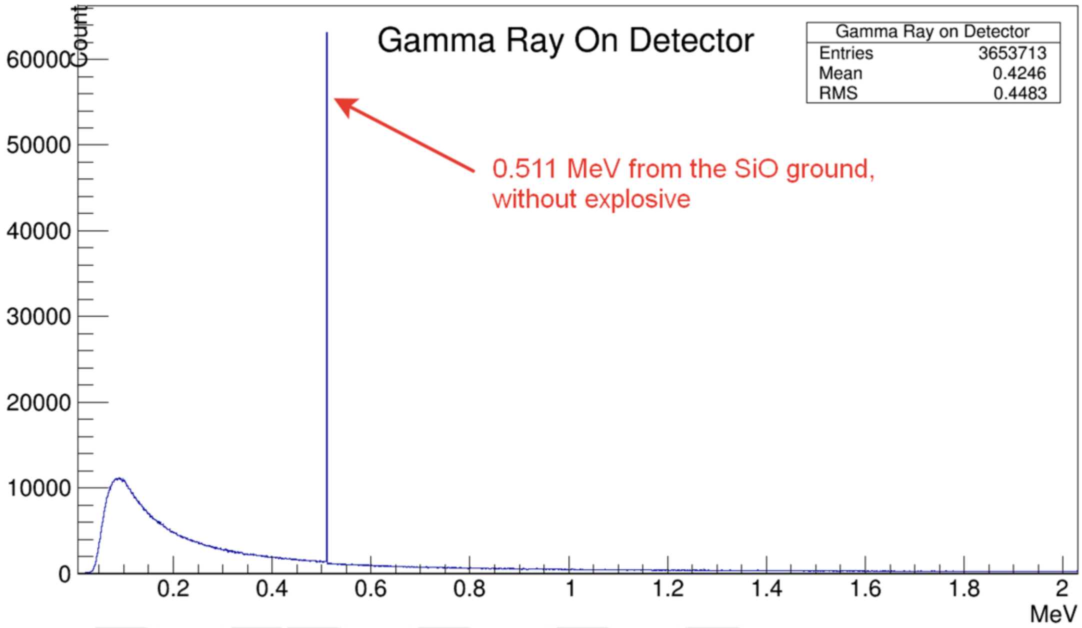

Figure 3.4 Gamma spectrum on the detector for SiO, without explosive.

Simulation predicted without any material inside the soil and the soil is assumed as a SiO composition. For a gamma spectrum, a peak is observed at 0.511 MeV (Figure 3.4). The observation of backscattered neutrons is given by Figure 9 is observed. 0.511 MeV Gamma peak in Figure 8 shows an annihilation radiation inside the soil, together with the second peak (around 0.1 MeV) and the tail has no distinctive peaks.

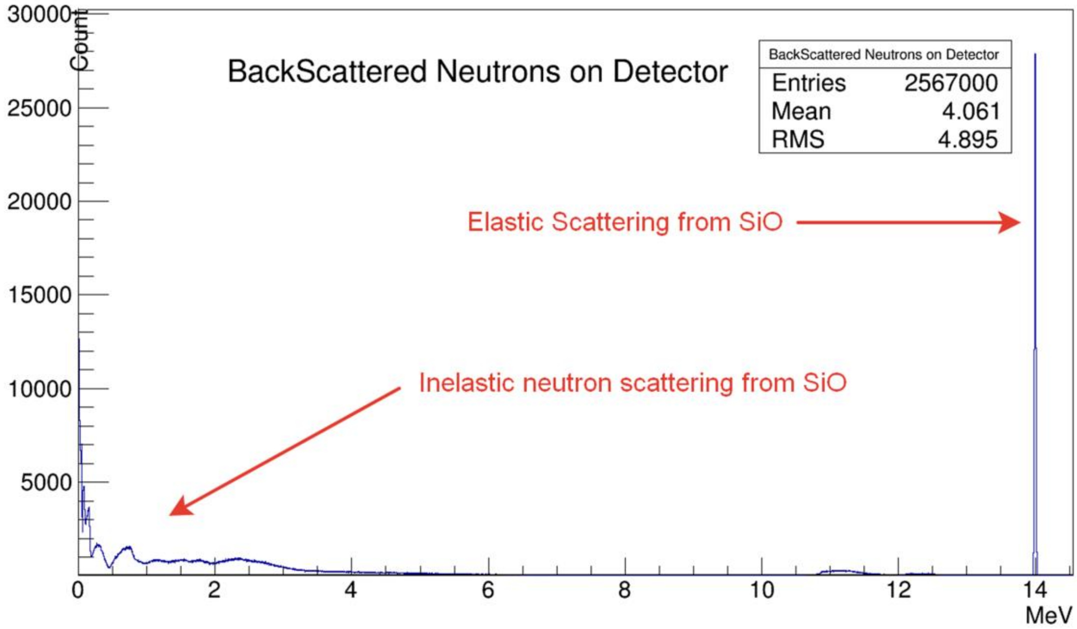

Figure 3.5 Back Scattered Neutrons energy from SiO.

%25 of neutrons are backscattered to the detector, both inelastic and elastic scattering behaviours are observed. The peak at 14 MeV shows elastic scattering, while the other forms are occured due to inelastic scatterings. After the simulation with only SiO, a hydrogen block is inserted into the soil with 2, 5, 10 and 20 cm depths.

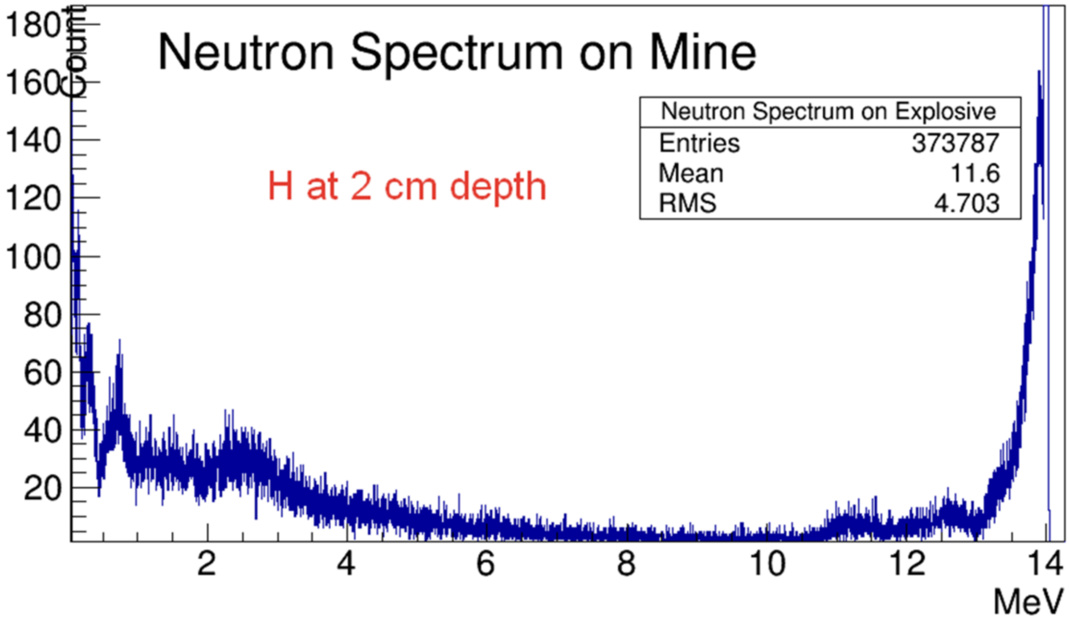

Figure 3.6 Neutron spectrum on the hydrogen block.

Figure 3.6 shows the neutron spectrum reached to the hydrogen block (at 2 cm depth), 1x10^7 neutrons generated from the source and 373787 neutrons are reached to the surface of hydrogen block.

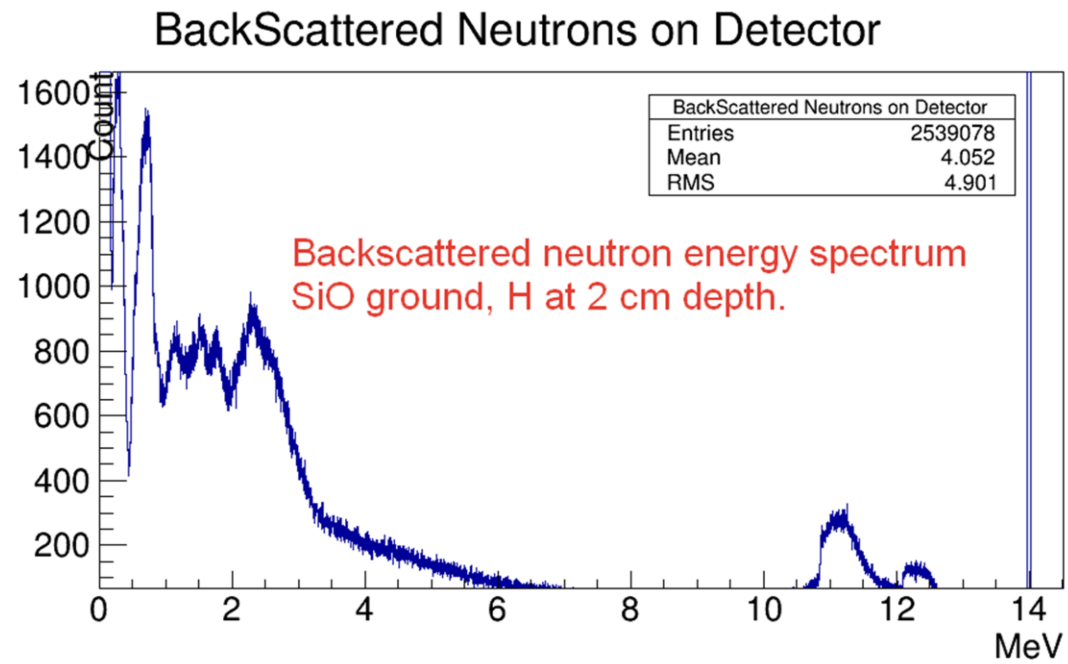

Figure 3.7 BSN on the detector, hydrogen block at 2 cm depth.

7859222 neutrons are reached to soil surface, and only 373787 of them can reached to the hydrogen block, 2539078 of neutrons are observed as backscattered. The number of backscattered neutrons without hydrogen block is 2567000. There is %0.9891 difference from the simulation which has no hydrogen block, which is distinctive feature to detect the material change under the detector system. (The counted neutron numbers seen on top right of the figures called as “Entries”)

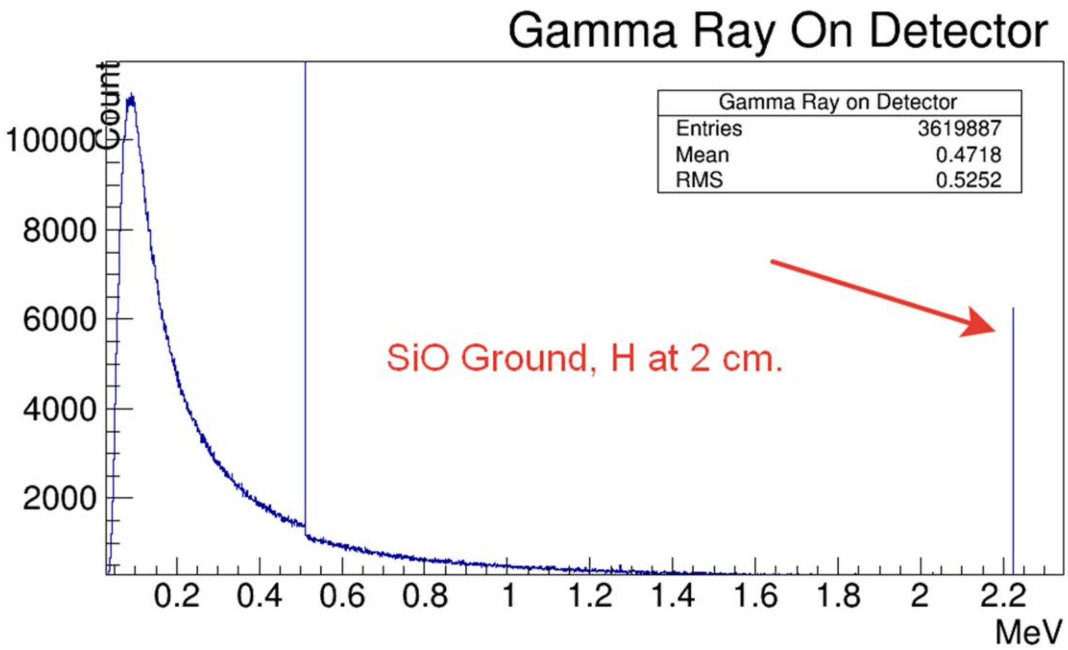

Figure 3.8 Gamma spectrum on the detector, hydrogen block at 2 cm depth.

From Figure 3.8 we see clearly a gamma ray at 2.21 MeV. It shows that, incoming neutrons creates new isotopes (deuterium and tritium) and this process releases the gamma ray during the decay. This is also a distinctive feature, because the hydrogen block depth is changed to 5 cm and the following properties are observed (Figure 3.9).

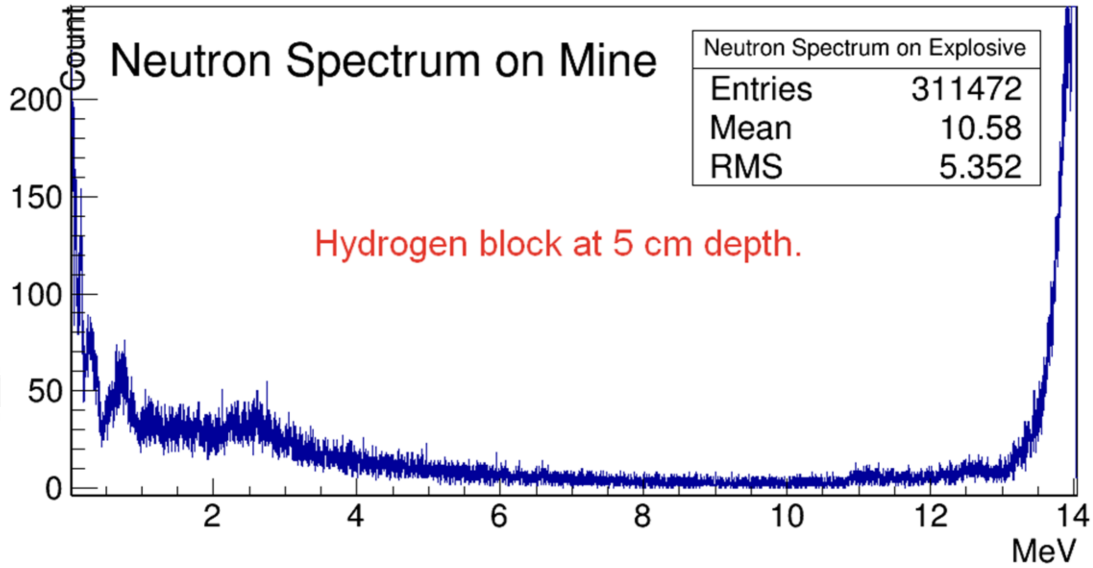

Figure 3.9 Neutron spectrum on hydrogen block at 5 cm depth.

From Figure 3.9, 311472 neutrons are reached to block surface in case of 5 cm depth, it was 373787 neutrons while the block at 2 cm depth. The number of reached neutrons decrease dramatically with the increasing depth, the reasons are the incoming angle of neutrons, and the surface area of block.

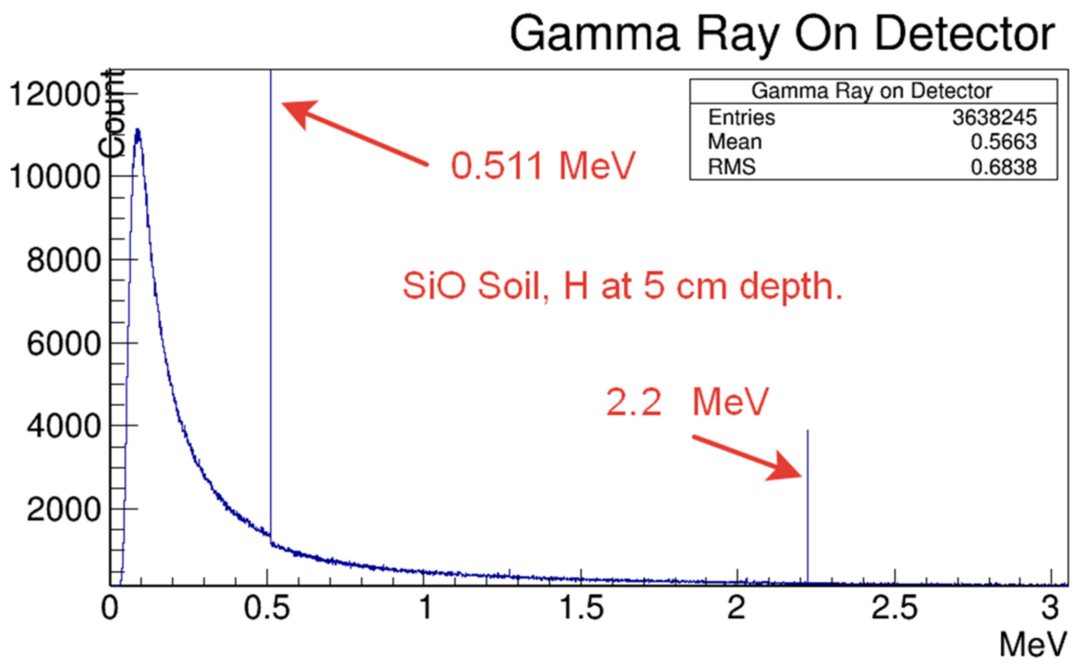

Figure 3.10 Gamma spectrum on the detector, hydrogen block at 5 cm depth.

In Figure 3.10, the peak still clearly is observed at 2.21 MeV leading a possibility of the measurement at 5 cm depth for gamma ray. The 5 cm limit is important, because the most of the APL mines buried above 5 cm.

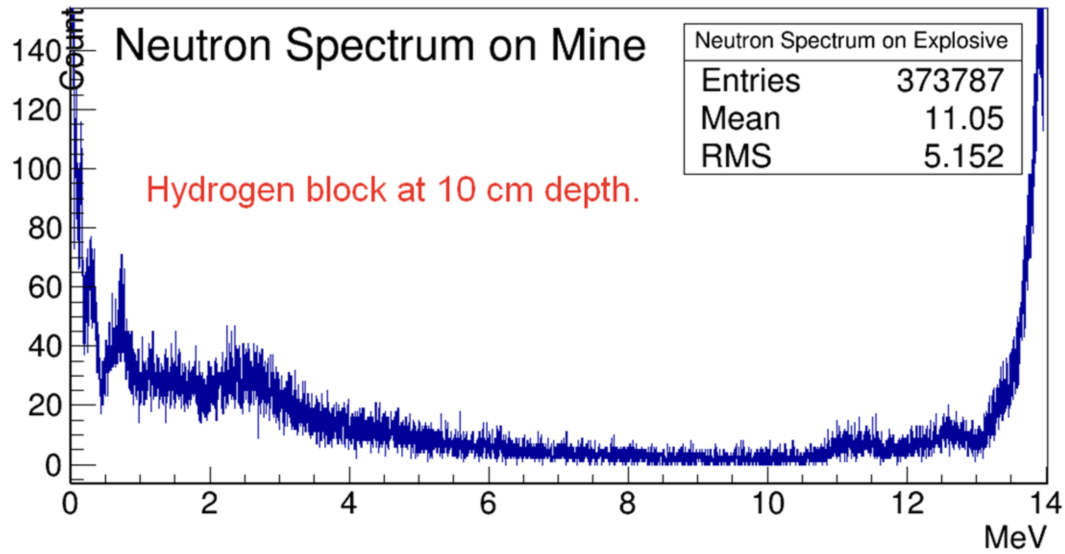

Figure 3.11 Neutron Energy Spectrum on the hydrogen block at 10 cm depth.

Similarly, the number of reached neutrons for 10 cm case is less than the number of neutrons for 5 cm, the reason is scatterings in the soil.

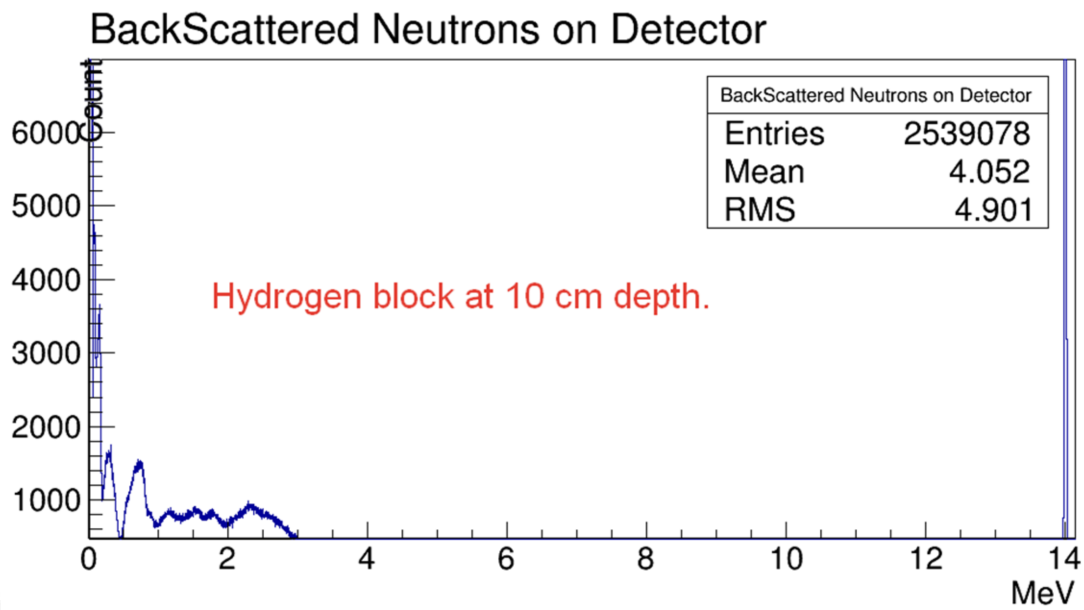

Figure 3.12 BSN on the detector, hydrogen block at 10 cm depth

From Figure 3.12, the number of backscattered neutrons still shows the material change in the soil. Hydrogen is still effecting the total backscattered neutrons going to the detector.

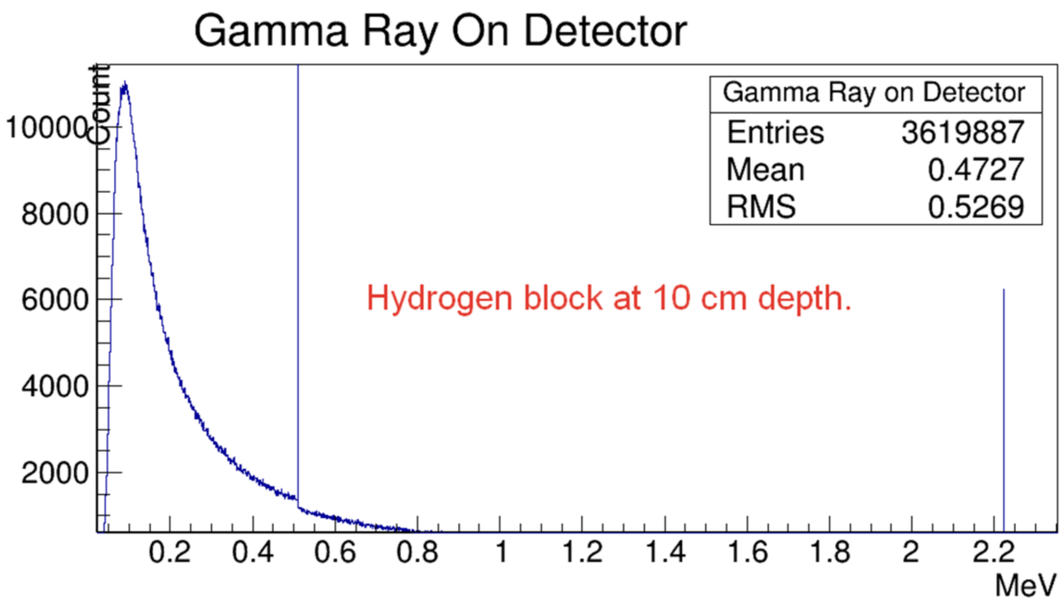

Figure 3.13 Gamma spectrum on the detector, hydrogen block at 10 cm depth.

From Figure 3.13, the peak at 2.21 MeV can be easily observed for 10 cm depth. When we move the block to the 20 cm depth, the following graphs are observed :

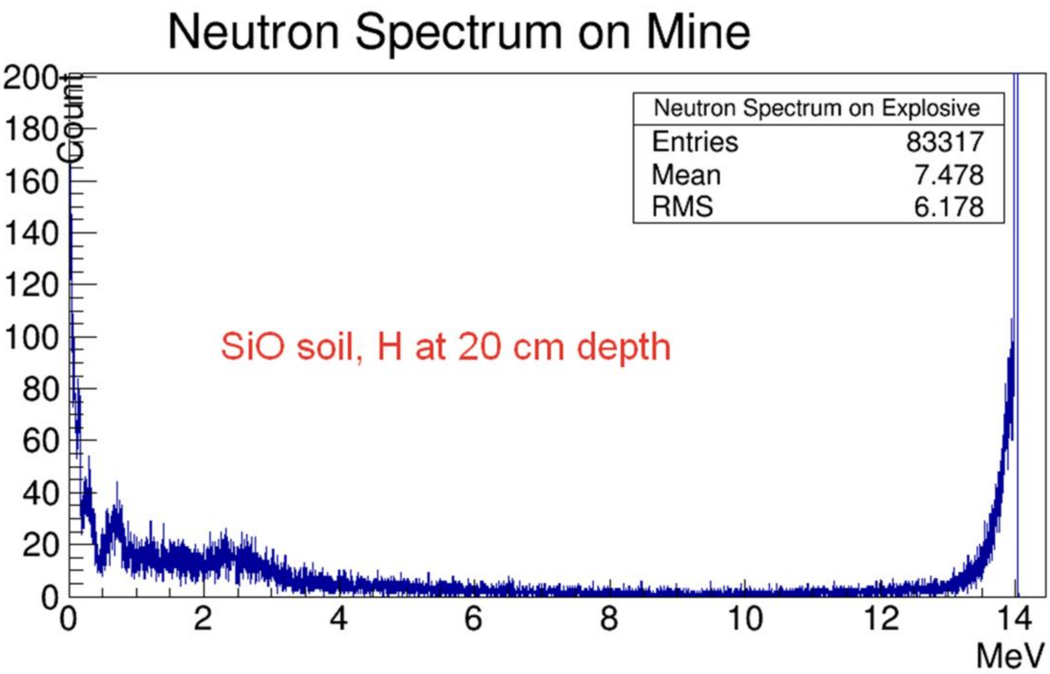

Figure 3.14 Neutron Spectrum on Hydrogen Block at 20 cm depth.

Only 83317 neutrons are reached to the block, which is less than the other cases.

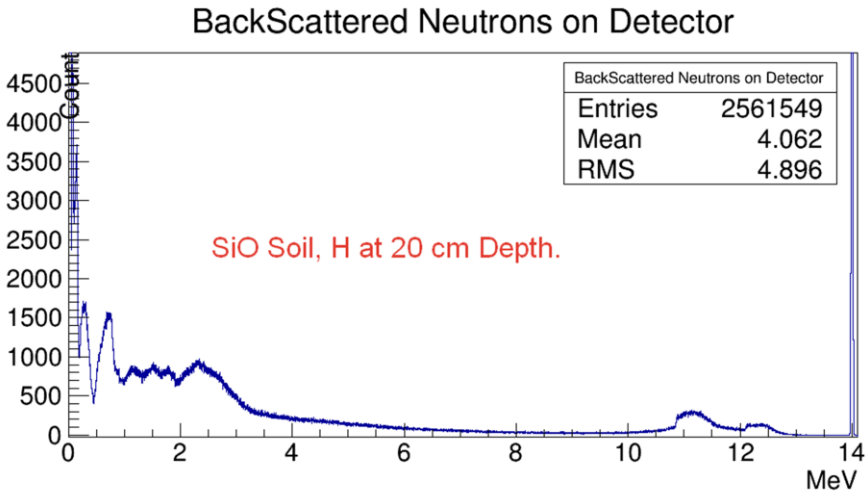

Figure 3.15 BSN on the detector, the hydrogen block at 20 cm depth.

The backscattered neutrons' difference from the first test simulation (simulation without hydrogen block) is less than %0.0023, for this ratio its hard to decide a certain material change inside the soil. The 20 cm distance can be used as a limiting factor for the test simulation.

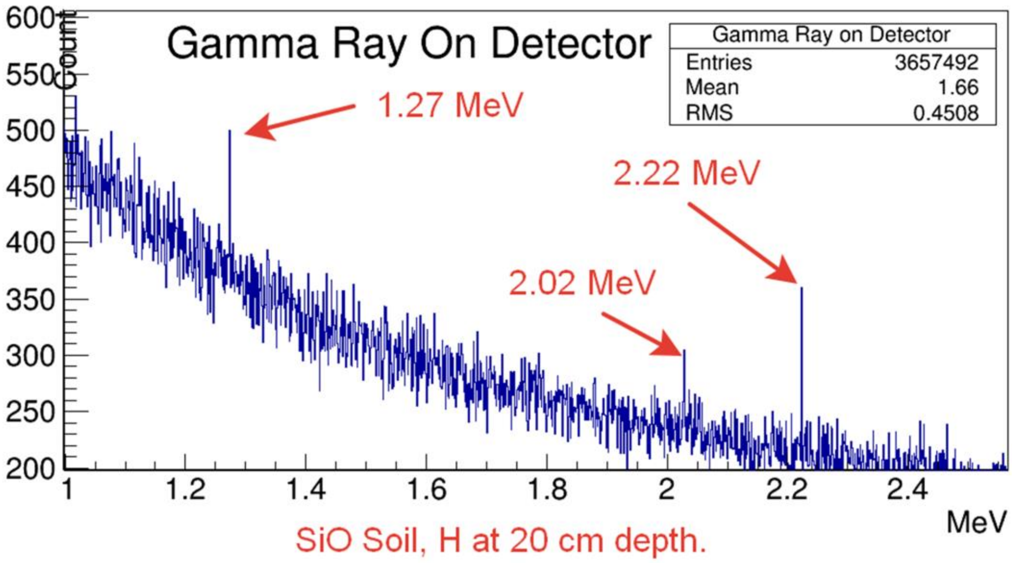

Figure 3.16 Gamma spectrum on the detector, hydrogen block at 20 cm depth.

For the gamma measurement, Figure 20 shows that the 2.21 MeV gamma peak is still observable, it is not a strong signal and not in the noisy area but measurable. The test simulation shows that up to the 20 cm the material difference is observable for both for neutron backscattering and neutron induced gamma emission.

3.6 Full Simulation with TNT and Real Soil Composition

In this section Trinitrotoluene (TNT) C7H5N3O6 is inserted into the soil which has %2.218 Hydrogen, %18.500 Nitrogen, %42.264 Oxygen and %37.016 Carbon with 1.65 g/cm3. For the soil type, HWSD tool is used.

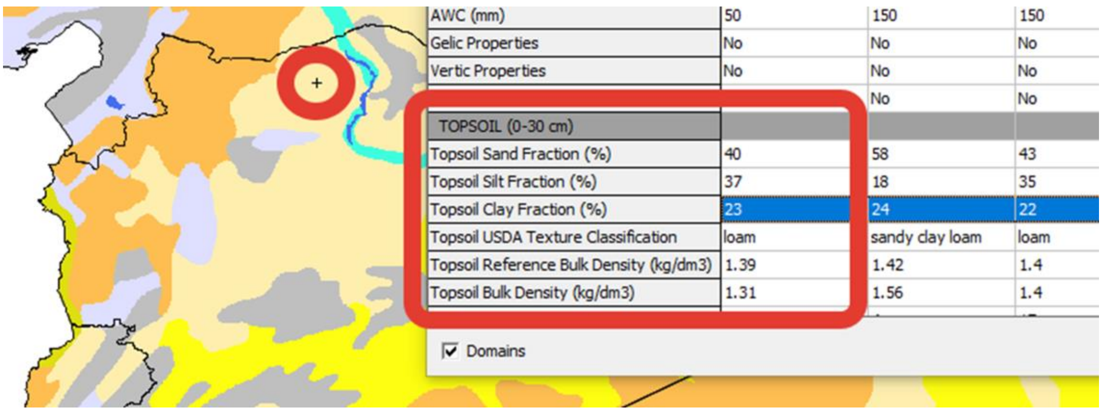

Figure 3.17 Soil properties at north Syria.

The point has %40 Sand, %37 Silt and %23 Clay with 1.39 kg/dm3 density properties which are inserted inserted into the soil properties of the Geant4 code.

1x10^7 Events are created without explosive, and the number of back scattered neutrons are 198783, which shows that approximately %19.8 of the neutrons are back scattered.

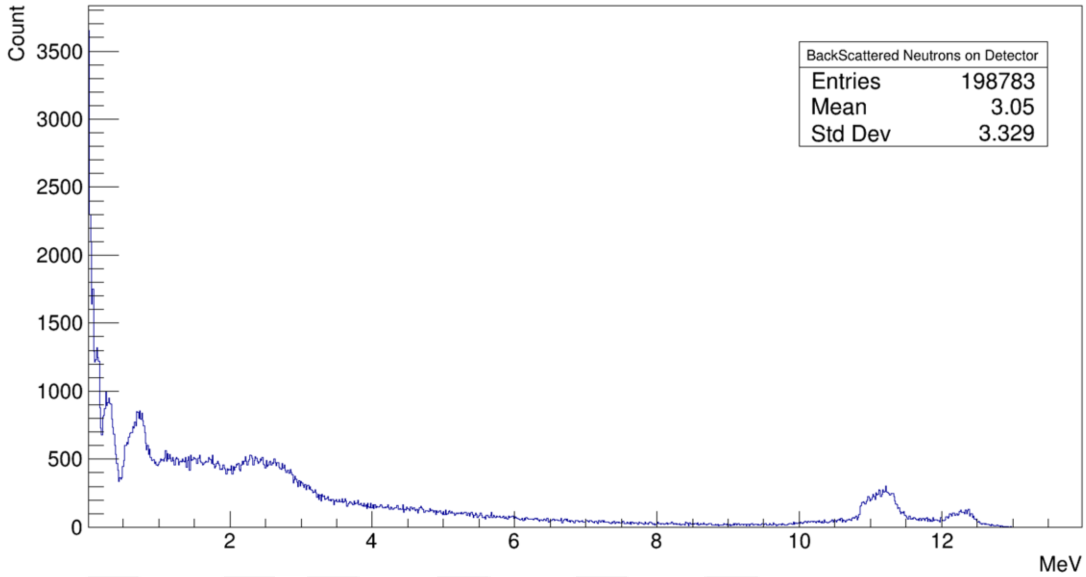

Figure 3.18 Back scattered neutron simulation from real soil composition.

The soil composition gives the following gamma spectrum (Figure 3.18), which is a similar spectrum as in Figure 8.

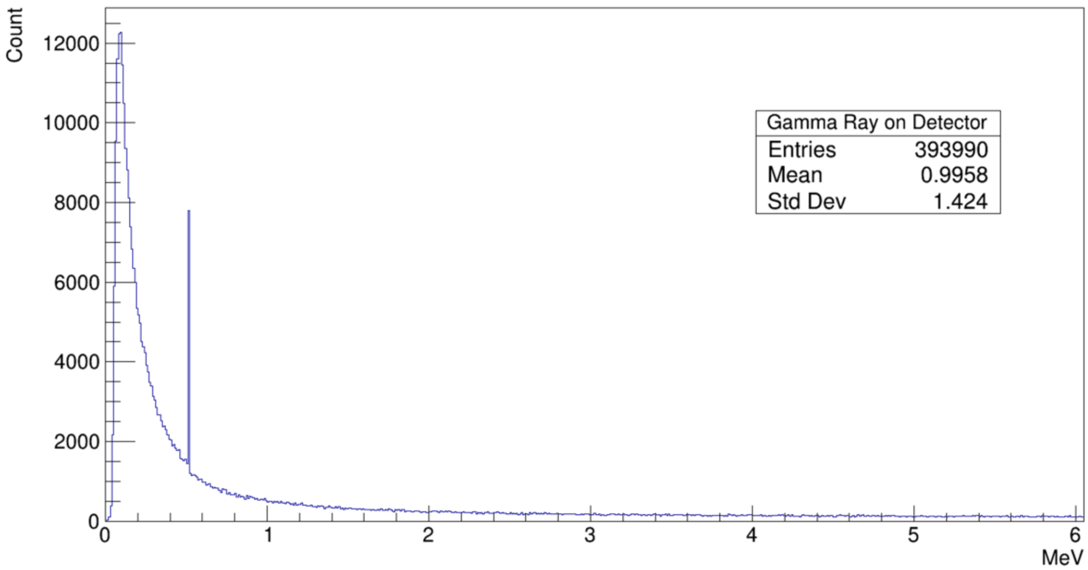

Figure 3.19 Gamma spectrum on the detector, real soil composition.

Figure 3.19 shows the calibration gamma output when a TNT composition is inserted (15x3 cm^3) top of the soil following outputs occur:

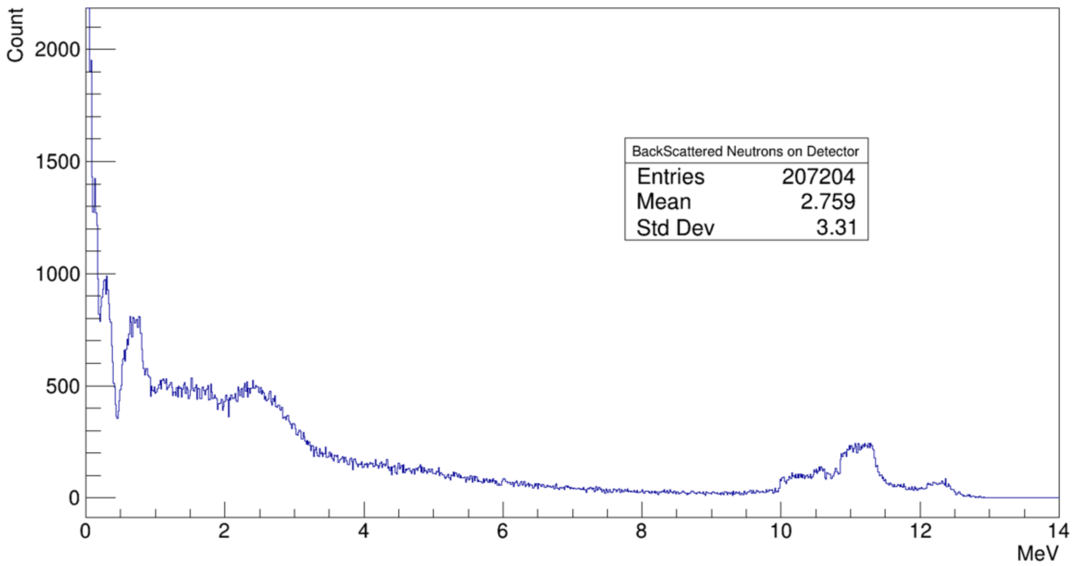

Figure 3.20 BSN on the detector, TNT inserted top of the soil.

Total number of back scattered neutrons are 207204 corresponding to %20.7, there is just %0.9 difference between the total number of back scattered neutrons. The neutrons spectra have similar characteristics.

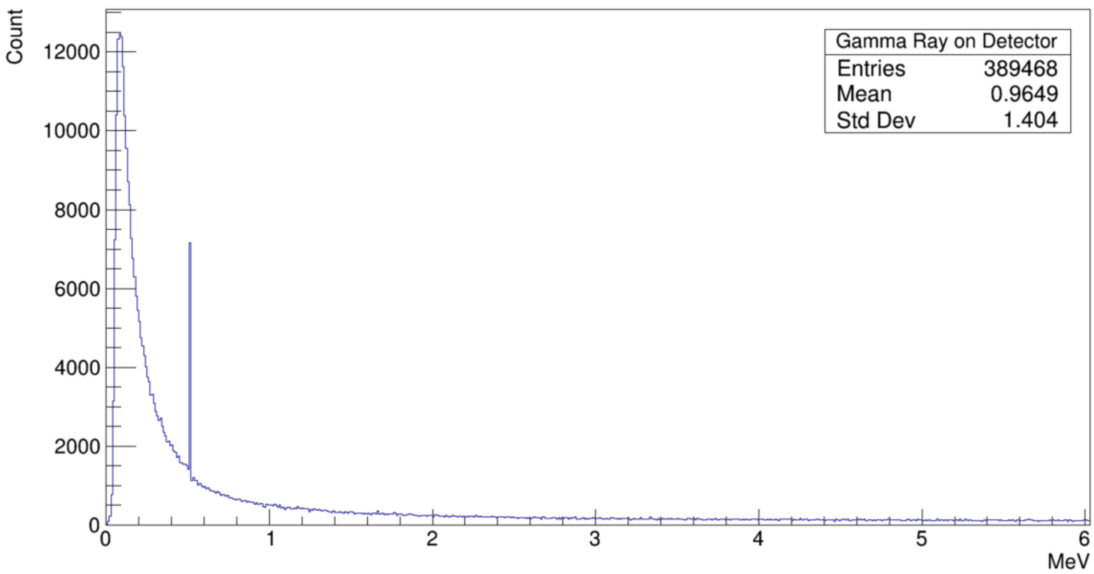

Figure 3.21 Gamma sepctrum on the detector induced by neutrons.

In Figure 3.21, no peaks are detected exclude the annihilation radiation at 0.511 MeV, which is the signal from the hydrogen source that could not be detected and lost in the spectrum. When TNT is moved to 10 cm depth distance, the total back scattered neutrons are 203435 (Figure 3.22) corresponding to %20.3 of the incoming neutron particles.

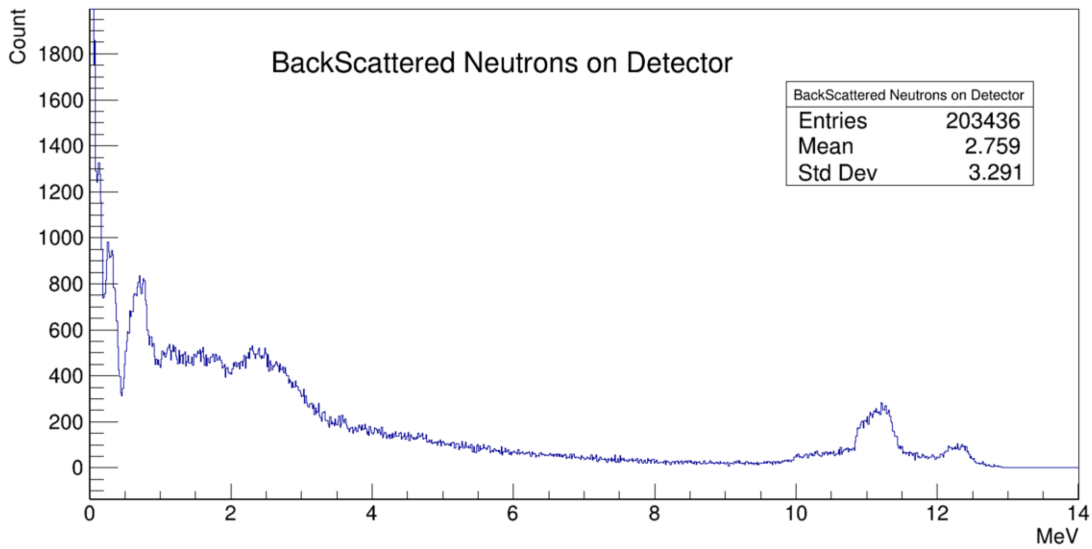

Figure 3.22 Back scattered neutrons from 10 cm depth TNT composition.

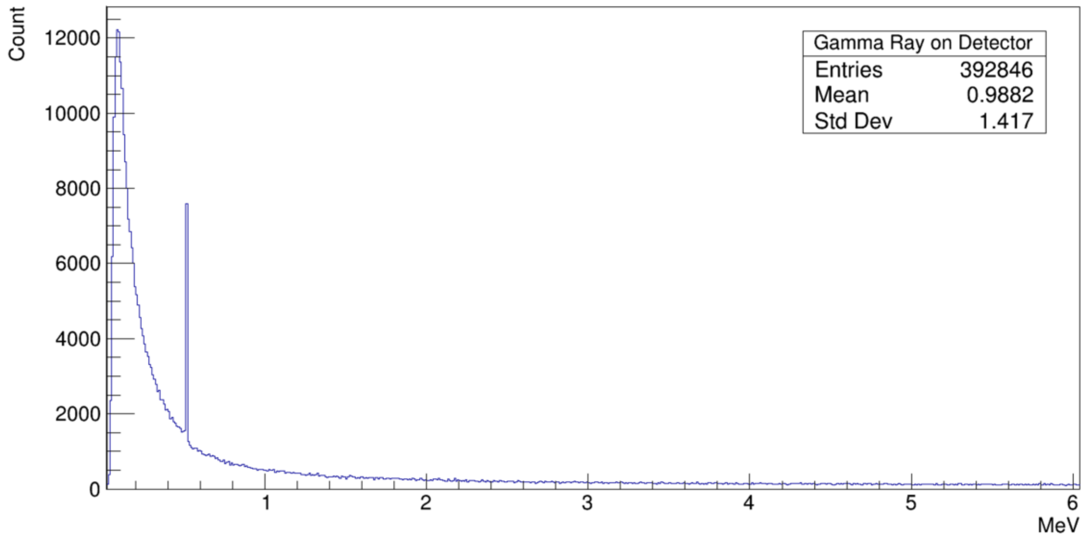

Figure 3.23 Gamma Spectrum on the detector for 10 cm depth TNT.

Similarly in Figure 3.21 and Figure 3.23, a significant signal could not be observed. At this point, the difference between the total number of back scattered neutrons still can be observable. When we move the TNT to 15 cm, the detector gets the following outputs :

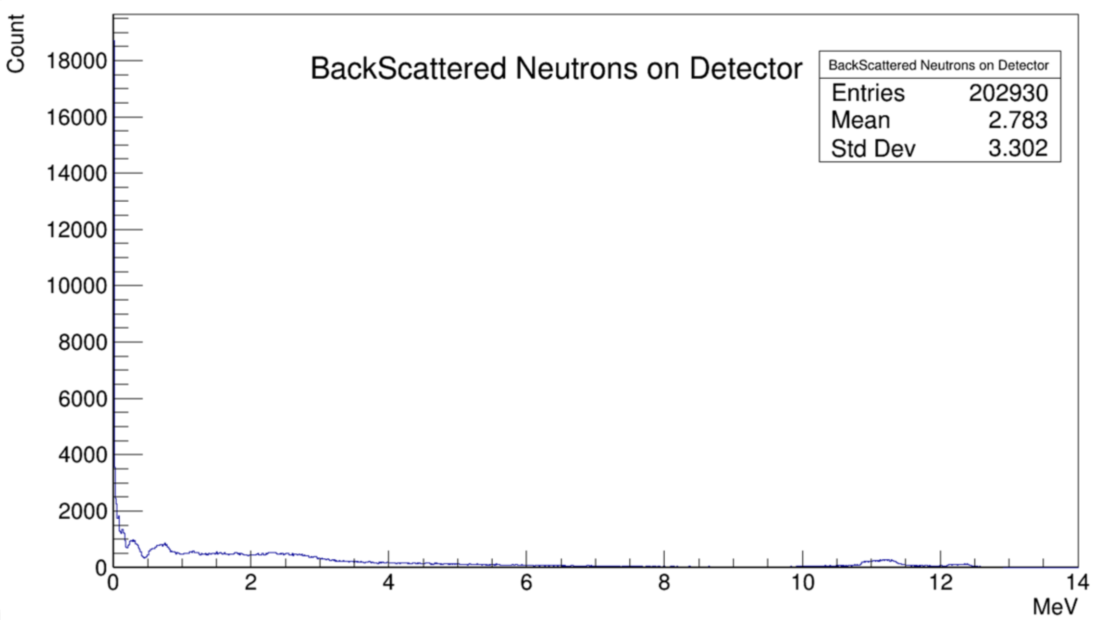

Figure 3.24 Back scattered neutrons on the detector when TNT at 15cm depth.

At 15 cm, the total number of back scattered neutrons are 202930 less than the previous case. The corresponding gamma spectrum is illustrated in Figure 3.25.

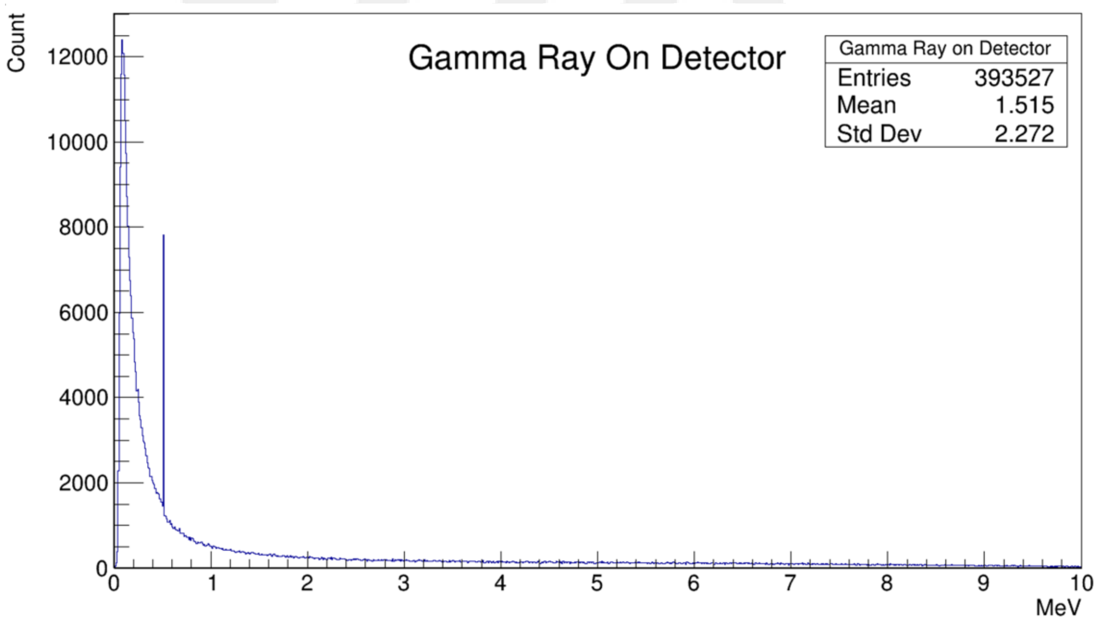

Figure 3.25 Gamma spectrum on the detector, when the TNT at 15 cm depth.

In the TNT simulation, neutron difference can clearly be observed but no gamma peaks can be detected for the hydrogen inside the explosive.

The summary of the back scattered neutrons for TNT is shown in the table below.

Table 3.2 Summary of neutron back scattering for TNT.

Without explosive	%19.8
When TNT at the soil surface	%20.7
When TNT at 10 cm depth.	%20.3
When TNT at 15 cm depth.	%20.2

3.7 Simulation for Tetrazene Explosive

The difference between the neutron ratio is less than %1, when we compare the full simulation with the another explosive Tetrazene (which contains %4.285 Hydrogen) the following outputs are observed :

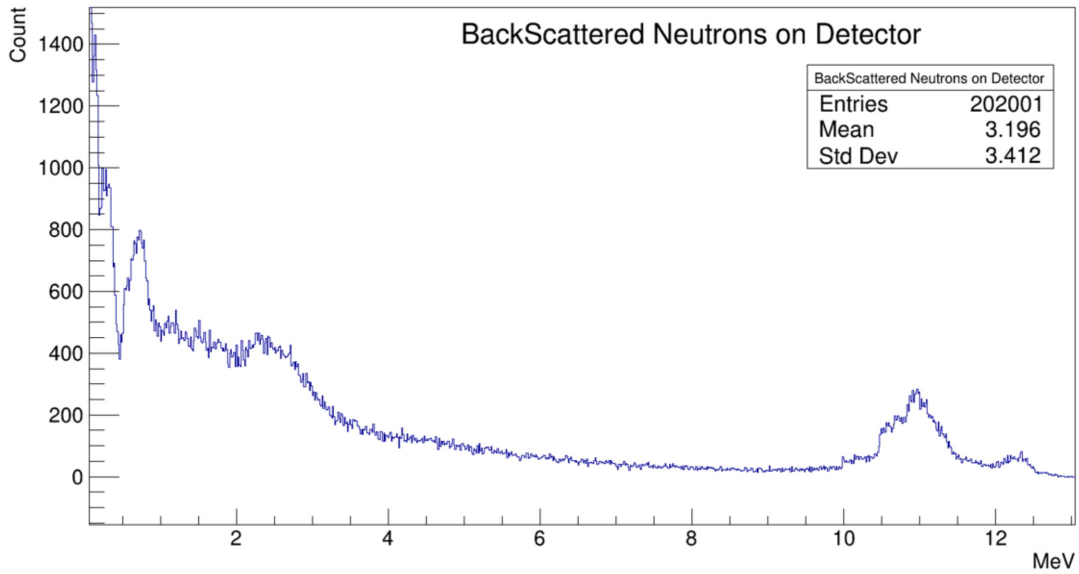

Figure 3.26 Back scattered neutrons when Tetrazene at soil surface.

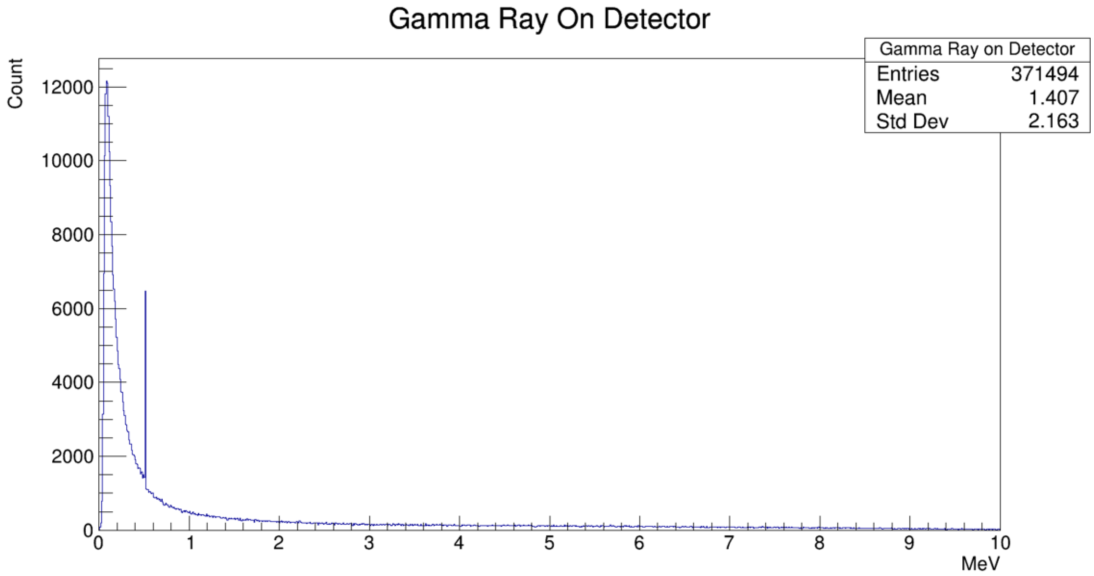

Figure 3.27 Gamma spectrum on the detector when Tetrazene at soil surface.

Tetrazene is a special explosive with one of the explosive which has a rich hydrogen concentration, but even for Tetrazene there is no observable peak for the hydrogen case. When tetrazene is moved to 10 cm depth, the following neutron back scattering graph occurs.

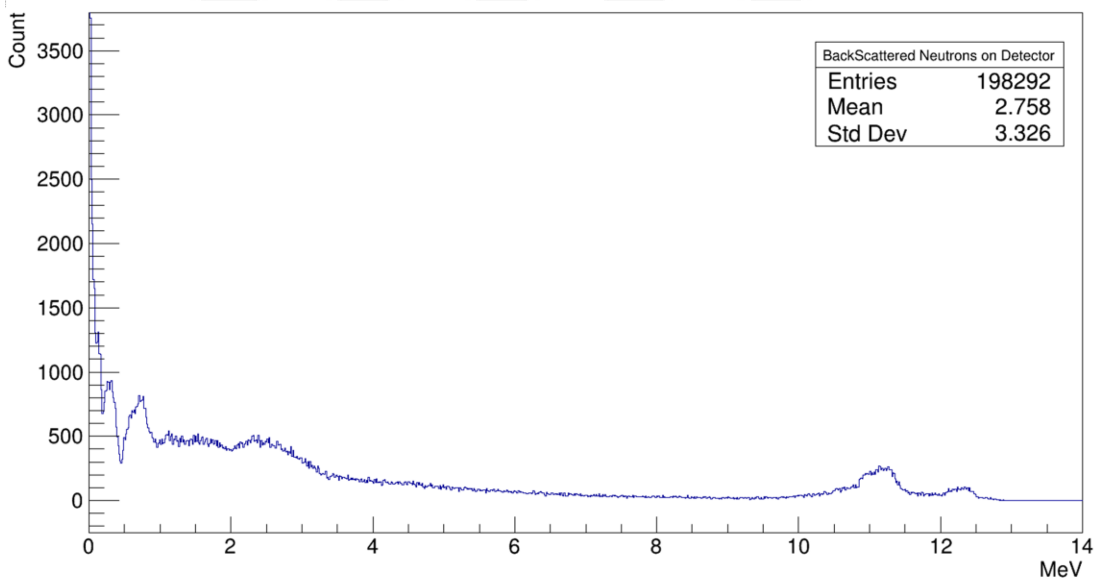

Figure 3.28 BSN on the detector surface when tetrazene at 10 cm depth.

Figure 3.28 shows that the total number of back scattered neutrons are 198292 which is very near to the ratio without explosive.

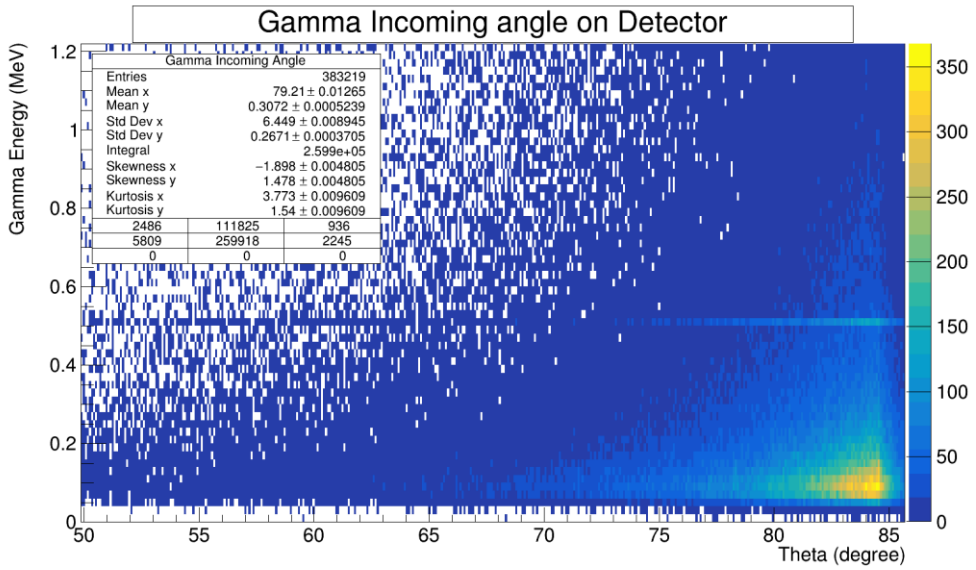

Figure 3.29 2D Histogram of Gamma Incoming Angle with Energies

The all results show that the back scattered neutrons are observable within a difference about %1 and gamma emissions to detect the hydrogen inside the explosive is not enough to find out explosive. All the simulations above, generated via single detector, using as possible as much detectors can increase the detection of back scattered neutrons ratio because of the resolution change. This issue is explained in the following chapter. In addition, the all of the observation throught our simulation have clarified that the codes used in the calculations work out in a reliable mood. Using these codes and the simulation introduced, we suggest a new technique for the detections of interest in the next chapter.

CHAPTER 4

A DETECTOR SUGGESTION FOR NEUTRON BACK SCATTERING

In the previous chapter, neutron back scattering with its energies has been observed, the back scattered neutron energies are found between 0 and 14 MeV, and Figure 9 has shown that the most of back scattered neutrons have almost the same energies. This explains that elastic scattering is the most observable behavior in this scenario.

Also Table 3.2 shows that, the number of back scattered neutrons for different depths are very close to each other. This situation requires precise detector systems. Using a new technology called as SiPM could make possible precise measurements with a high resolution. SiPMs are parallel connected avalanche photo diode arrays within a small areas such as 1x1, 2x2, 3x3 mm.

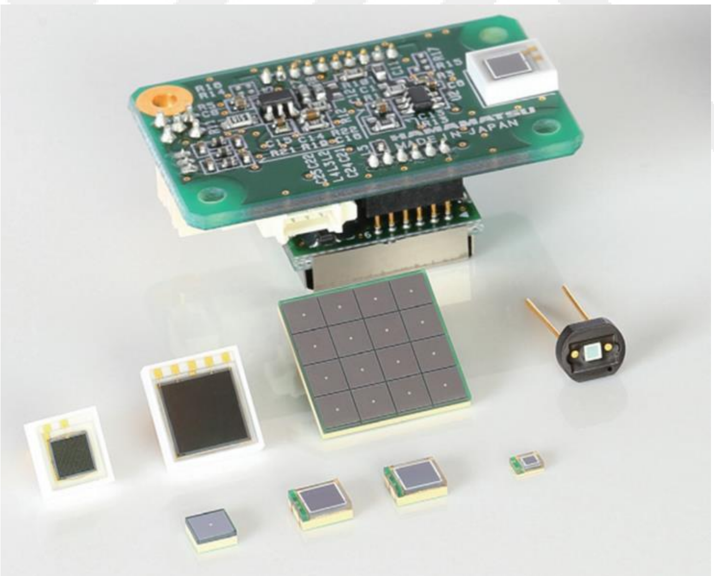

Figure 4.1 Silicon photo multiplier examples.[12]

SiPMs in reality not developed to directly measure a neutron particle, it measures in fact photons within a certain range, to detect a neutron; neutron should create a photon with a suitable wavelength for target SiPM. The light emitting materials called as scintillators.

4.1 Scintillators for 14 MeV Neutrons

Scintillators are light emitting materials in the case of a charged particle interaction, therefore emitted light wavelength depends on scintillator/crystal and incoming particle types, together with its energy. In the light of all these, a new approach to detect a buried APL is discussed in detail in the previous chapter, which requires a neutron source with a properly chosen energy considering the necessary interaction between the neutron particles and the crystal.

In the simulation environment, due to its portability and high neutron energy peak, neutron generators are used. Such generators are also employed as neutron source for many areas as initiating a reaction in nuclear reactors, neutron spectroscopy, neutron diffraction etc. In addition, they are also widely used in industry to measure distances to calculate raw material stuff in silos and deep sets.

Lanthanum Bromide (LaBr3(Ce)) is one of most known scintillator used in SPECT, security, oil & gas exploration fields. For 14 MeV neutrons, it has overall 43% efficiency and it emits an intense peak at 0.511 MeV with an annihilation between 14 MeV neutron and Lanthanum Bromide**[**13**]**. 0.511 MeV annihilation radiation is also used in medical applications such as PET and there are several scintillators developed for accurate measurements.

To detect a 14 MeV neutron via 0.511 MeV gamma annihilation, the following steps occur :

1. 14 MeV neutrons interact with Lanthanum Bromide and they create 0.511 MeV gamma ray.
2. 0.511 MeV gamma rays interact with one of coupled scintillator (NaI(Tl), BGO, LSO , YSO, GSO or BaF2)
3. Coupled scintillator emits photon to SiPM.

Table 4.2 shows the most probable photon wavelengths for 0.511 MeV gamma rays for the coupling scintillators.

Table 4.1 Scintillators for detecting 0.511 MeV Gamma rays.[14]

Property	NaI(Tl)	BGO	LSO	YSO	GSO	BaF2
Density (g/cm3)	3.67	7.13	7.4	4.53	6.71	4.89
Attenuation length	2.88	1.05	1.16	2.58	1.43	2.2
Decay constant (ns)	230	300	40	70	60	0.6
Light output (photons/keV)	38	6	29	46	10	2
Relative light output	100.00%	15.00%	75.00%	118.00%	25.00%	5.00%
Wavelength ^(nm)	410	480	420	420	440	220
Index of refraction	1.85	2.15	1.82	1.8	1.91	1.56

The wavelengths are observed between 220 to 480 nm. So, the SiPM should have a detection efficiency peak at one of the wavelengths in the table to build a correct coupling between Lanthanum Bromide, second scintillator and SiPM.

4.2 Detecting Photons with SiPMs

In general SiPMs work within violet/ultra violet wavelength ranges, which has a photo detection efficiency peak at 550 nm and %30 efficiency about 480 nm as shown in Figure 34. It is suitable to use such SiPMs with BGO crystal scintillators.

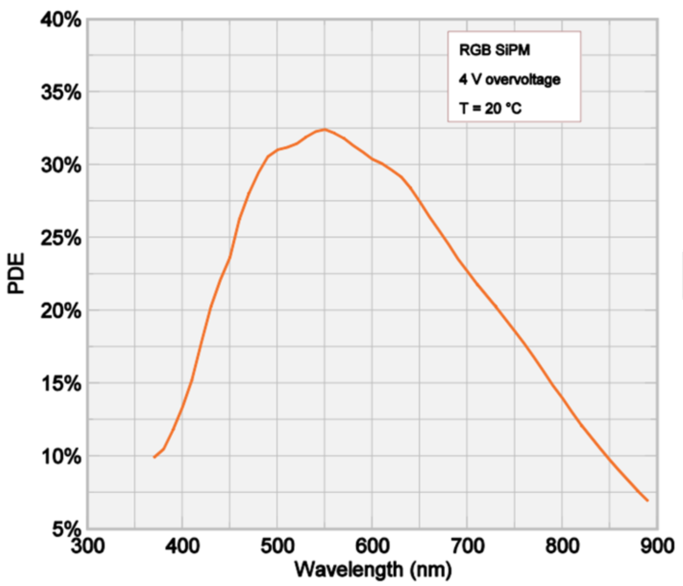

Figure 4.2 Photo detection efficiency (PDE) in RGB-SiPMs.[15]

Due to SiPMs small sizes, it is recommended to use sets of SiPMs as an array. SiPM arrays commercially available, using more than one SiPMs can achieve monitoring neutrons as two dimensional views.

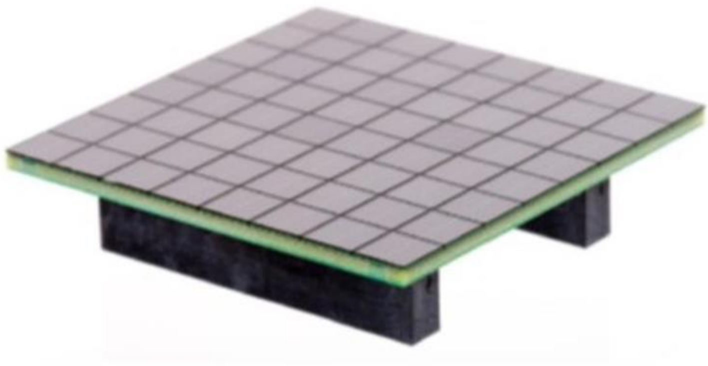

Figure 4.3 An example of SiPM array.[16]

SiPMs also require electronic equipment to analyze signals created by photons, typically SiPM give an analog output about 0-100 mV within 300 nanoseconds. The signal should be amplified, shaped before digitizing/analyzing. For this purpose, following approximations can be used :

1. Using Nuclear Instrument Modules (NIM) or Versa Module European (VME) modules for amplifying, shaping signals.
2. Using SiPM Readout front end boards such as CAEN – A1702 [17].
3. Using special Application Specific Integrated Circuit (ASIC) devices such as Weeroc - Citiroc 1A [18].

For laboratory research and testing, first two approximation is suitable for test purposes. For developing a complete detector solutions its recommend to build specific boards with ASIC devices like Weeroc – Citiroc 1A.

After amplification and shaping process the signal should be digitized to analyze, at this point there are two ways.

1. Using a commercially available digitizers for developed SiPM signal analysis . (for example: CAEN – DT5730 [19])
2. Developing application oriented digitizer with Field Programmable Gate Arrays (FPGA) and digitizer ASICs (for example : PSI – DRS4 chip [20]).

Entry 1 in above is easily possible for research purposes, entry 2 is a hard but required way for a portable neutron back scattering measurement. After building/set-up electronic equipment, an analyzing software should be developed for multi SiPM signals.

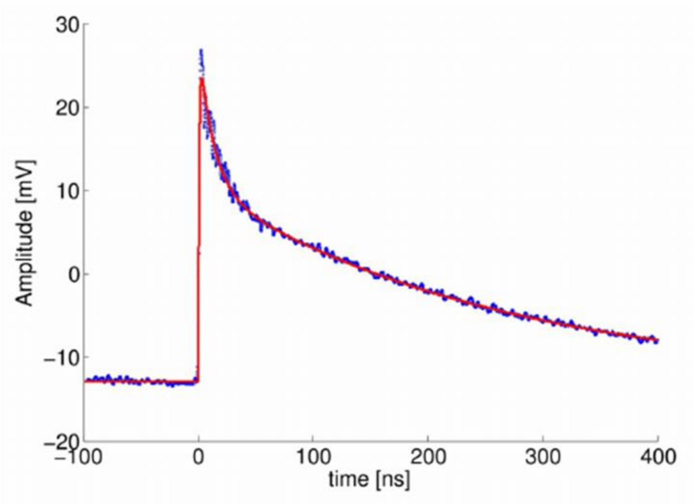

Figure 4.4 A SiPM Signal waveform.[21]

Figure 36 illustrates a general type of SiPM signals. Signal peak, tail and trajectory from peak to end of the tail depend on incoming photon number and energies. The corresponding energy of the signal should be calculated by digital pulse processing techniques. The methods listed below are different ways to define the energy of the signal.

- Pulse height analysis
- Pulse shape discrimination

Pulse height analysis (PHA) calculates activated number of SiPM photo diodes at the same time (which means the peak signal) and pulse shape discrimination analyses having a complete form with its tail via integrating the waveform. The second option gives more accurate outputs for SiPM signals.

Also, following applications can be used to controlling SiPM and visualize signal outputs.

- NI – Labview : A software platform for controlling electronic devices with an easy user interface and graphical programming language [22].
- Kitware – Paraview : A data analysis software for visualization and filtering raw data [23].

This novel suggestion covers an alternative treatment for the APL landmine detector system, which could give number of the backscattered neutrons with high resolution.

CHAPTER 5

DISCUSSION AND CONCLUSION

In this work, 14 MeV-neutrons have been used as a source to detect neutron back scattering and gamma emissions from the soil and explosive (for TNT and Tetrazene) to reach until 20 cm depth of the soil. 14 MeV-neutrons lose their energy while traveling in the soil and make possible to observe the all possible reactions between neutrons and target materials. Number of back scattered neutron ratio increase when an explosive inserted into soil. The difference of back scattered neutron ratio observed between explosive buried soil and the usual soil is about %1 when the TNT at the surface. A single detector used for the simulation, increasing resolution via multi minimal detectors can be increased that ratio. A detector system has been suggested at Chapter 4 to overcome this issue.

Most of the known mine explosives are consist of hydrogen, nitrogen, oxygen and carbon materials. The materials also can be found in air and inside the soil, ratio of the materials inside the soil and air changes area to area. To find the best solution, a known area's soil properties have been applied to soil definition in the code and Geant4_Air definition has been used to define the air. Gamma peaks are observable when a full hydrogen block is inserted into the soil, however the hydrogen ratio in explosives are %5 or less. The same peaks could have not been observed for a real explosive simulation. Gamma spectrum of the usual soil and explosive buried soil are not feasible to detect clear signals unlike the neutron back scattering which is feasible.

In the previous works, limestone has used as soil composition in general, and consequently the simulations were detected C, H, N, O materials inside the limestone. However, in reality soil compositions consist of sand, silt, clay with different percentages. All these conditions therefore make a challenge to detect explosive.

The simulation shows that, neutron based back scattering technique needs very accurate detection system when compared to the conventional He3 detectors with huge sizes that are not agreeable to use for detection purposes.

To detect neutrons, there are several other methods. As a new technology called as SiPM (Silicon Photo multiplier) makes possible to detect very weak light signals with high resolution and accuracy along this line. Unlike the classic photo diode tubes, its small size makes possible to detect photon activities for very small areas. Every parallel connected photo diode behaves like a geiger mode photon counting diode and there are two possible signals for each cell, 1 or 0. Incoming light intensity effect the total activated cells and they create an analog signal. A high resolution SIPM can be used with sensitive neutron scintillators which are light emitting materials creating photon particles when a radioactive particle interacts with it. Instead of using single or a few detectors, a set of small detectors could give more information rather than the standard ones.

Overall, the work presented in this thesis has cleared out some interesting questions such as

- Can the detection distance affects the results ?

(Answer : Yes, the best measuring distance should be as possible as near to the ground. However, this method may not be suitable for bumpy areas.)

- Is the new suggestion applicable?

(Answer : It is recommended to use such system with the support of another anti personnel landmine detection system, a hybrid detector system can be applicable with high resolution detector systems such as SiPM leading to high resolution detector systems.)

- Can humidity or snow block the detection method?

(Answer : Yes, it can affect. Both humidity and snow consist of hydrogen and it can create more intense neutron back scattering to detectors. At the data analysis phase, using filtering algorithms may aim to bypass humidity/snow effects.)

- Is neutron sources suitable to continuous usage?

(Answer : No, commercial neutron generators have working time limits up to thousands of hours.)

As a final remark, a simulation software has been developed in the present work for APL explosive detection through investigating back scattered neutrons and gamma emissions from real soil compositions and explosives. The results obtained showed that neutron back scattering is applicable to detect explosives up to 20 cm depths. The overall difference between the normal soil and explosive buried soil neutron back scattering ratio is about %1. This is relatively small ratio and needs a new detector system instead of conventional approximations. Gamma emissions for material definition is also simulated, the emissions from the explosive is observed as defective to define material under the soil.

A new detector system discussed here has been suggested to monitoring neutron back scattering as imaging the soil field with SiPM technology. This neutron radiography system could possibly overcome the low resolution and back scattering ratio problem.

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