Geant4 simulation of the dual phase Time Projection Chamber TPC of argon to detect neutrinos

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Abstract. The present work describes the simulation carried out in Geant4 of a Time Projection Chamber TPC of argon that uses not only a dual-phase technology (liquid and gas) but also PhotoMultiplier tubes PMT for the detection of scintillation caused by the interaction of charged particles with argon. Furthermore, the optoelectronic characteristics of the PMT are analyzed. This allows the study of particles production through the neutrino-nucleus interactions.

Keywords: Neutrinos, Time Projection Chamber, Photomultiplier tubes, ionizing particles.

1. Introduction
The study of neutrino interactions, in general, has played a tremendous role in testing the validity of several models of the electroweak weakening theory. In particular, the weak neutrino-nucleus interactions involving the associated exclusive production of stranger particles in the medium energy region have become one of the main theoretical and experimental topics in the fields of astrophysics, cosmology, particle physics and nuclear.

Neutrino experiments in general have two different simulation phases. The first simulates the line of light system that produces the neutrino flux of the primary protons and the second models the resulting energy deposits in the detector after the neutrino has traveled from its origin to the detector and interacted with a nucleus or electron objective [5]. The realms of each phase can be very different in the modeling needs of physics. For this we need a new generation of highly sensitive and high resolution detectors for neutrino-matter interaction. A novel detector is a Time Projection Chamber TPC.

2. Basic information of the dual phase Time Projection Chamber
The dual-phase TPC that uses liquid argon with a gaseous phase in the upper part as the active volume to detect scintillation and ionization signals created within the liquid Argon by incoming particles, as shown in figure 1. In the interface there is a mesh with special properties of a Large Electron Multiplier in order to amplified the signal in S2.
2.1. Large Electron Multiplier
The electron multiplier amplifies the signal that was initially sent to the detector that has upper and lower electrodes and are located at the interface between the liquid and gaseous argon and follow the following steps:

- The ionization electrons move towards the liquid surface of the argon.
- Extraction of electrons from liquid phase to gas through a grid.
- Multiplication of charge: LEM - and then load collection in the anode reading (2 orthogonal views) (without induction plane)

Figure 1: Sketch of the operating principle of the dual phase TPC of Argon

Figure 2: Extraction of electrons from liquid to gas phase through a Large Electron Multiplier LEM.[3]
2.2. Liquefied noble gases as neutrino target

From all noble elements, only argon and xenon are currently used as targets for dark matter detection. Neon has been suggested as a medium for low-energy neutrino detection, and could potentially be employed in the search for neutrinos. In their liquid phase, noble elements are excellent media for building large, homogeneous, compact and self-shielding detectors. Liquid xenon (LXe) and liquid argon (LAr) are excellent scintillators and good ionizers in response to the passage of radiation. The simultaneous detection of ionization and scintillation signals allows to identify the primary particle interacting in the liquid, for the ratio of the two observables depends on dE/dx [4]. Argon has been chosen for its low price and abundance in the atmosphere.

Table 1: Physical properties, volume fraction in the atmosphere and radioactive isotopes of the noble elements.[4]

| Property [unit]                  | Xe       | Ar       |
|---------------------------------|----------|----------|
| Atomic number                   | 54       | 18       |
| Mean atomic weight              | 131.3    | 40.0     |
| Boiling point $T_b$ at 1 atm [K] | 165.0    | 87.3     |
| Melting point $T_m$ at 1 atm [K] | 161.4    | 83.8     |
| Gas density at 1 atm & 298 K [g/l] | 5.40    | 1.63     |
| Gas density at 1 atm & $T_b$ [g/l] | 9.99     | 5.77     |
| Liquid density at $T_b$ [g/cm$^3$] | 2.94     | 1.40     |
| Volume ratio                    | 526      | 795      |
| Dielectric constant of liquid   | 1.95     | 1.51     |
| Volume fraction in Earths atmosphere [ppm] | 0.09 | 9340 |
| Radioactive isotopes            | $^{136}$Xe, $T_{1/2} = 2.16 \times 10^{21}$ yr | $^{39}$Ar, $T_{1/2} = 269$ yr |

2.3. Scintillation and ionization

According to [2], the argon scintillation process consists of different reactions. Briefly, the scintillation light is emitted by a state of argon dimer excited ($Ar^*_2$) that decomposes to the ground state. This state of arousal can be created in two different simultaneous reactions. The first reaction begins with an atom of argon excited, produced after the process of dispersion with the incoming particle, as an initial condition.

\[
Ar^* + Ar + Ar \rightarrow Ar^*_2
\]
\[
Ar^*_2 \rightarrow 2Ar + h\nu
\]  

The second reaction is a collection of several reactions after an initial ionization:

\[
Ar^+ + Ar \rightarrow Ar^+_2
\]
\[
Ar^+_2 + e^- \rightarrow Ar^{**} + Ar
\]
\[
Ar^{**} \rightarrow Ar^* + heat
\]
\[
Ar^* + Ar + Ar \rightarrow Ar^*_2 + Ar
\]
\[
Ar^*_2 \rightarrow 2Ar + h\nu
\]  

As can be seen in these scintillation reactions, one can delineate that argon is transparent to its own scintillation photons since the photons produced are emitted by an excited dimer state,
so that scintillation light is not absorbed by other atoms of argon. The average energy required to produce a scintillation photon in liquid argon is \( W = 23.6^{+0.5}_{-0.3} \text{eV} \) [6].

When applying the electric field of drift, the second line in the reactions in the equation 2 is suppressed and a part of the electrons produced separates from the ions, thus being lost for the recombination process. Due to the amplification of the ionization signal by the electric field, signal S2 is always much larger than S1. With the relation of \( S2/S1 \), which is always lower for nuclear setbacks than for electronic setbacks, it is possible to perform a background discrimination of the electronic and nuclear recoil [2].

3. Analysis of dual-phase Time Projection Chamber

3.1. Light Collection Efficiency LCE

To extract the LCE from the simulation data for each tracked particle, an additional program is developed for the analysis, which divides the TPC into volumes and evaluates the LCE as the PMT fraction coincides with the number of fully created photons in each volume. To obtain the LCE of the TPC, \( 10^9 \) optical photons with an energy of 7 eV are simulated. These optical photons are uniformly distributed and connected to the volume of liquid argon. The absorption length of liquid argon is set at 20 cm and the reflectivity of Polietetrafluoroetileno PTFE is implemented at 95 \%. In addition to this, another geometric effect must be considered.

However, grids can not be implemented directly in GEANT4[1], the meshes of the grid in the simulation are added as a solid volume with properties of a grid. That means meshes have a refractive index that controls the permeability. This induces different refractive indices for meshes surrounded by different volumes. If this is not considered and an adequate refractive index is not used, the photons will no longer pass the mesh.

The absolute LCE can be obtained from the MonteCarlo MC in the following way (where \((x,y,z)\) is the corresponding Bin):

\[
LCE(x,y,z) = \frac{N_{detected}(x,y,z) \cdot QE \cdot CE \cdot QE_{increase}}{N_{generated}(x,y,z)}
\]

- \( N_{detected}(x,y,z) \): The number of photons generated at \((x,y,z)\) and hitting a PMT photocathode (are registered by the PMTHitCollection) corrected by the PMT QE and CE (90)
- \( QE \): Quantum Efficiency which has to be applied per-PMT.
- \( N_{generated}(x,y,z) \): The number of photons generated at \((x,y,z)\).
- \( CE \): Collection Efficiency of the PMTs (from the photocathode to the first dynode).

3.2. Calculation in the source code

The simulations are performed with 1 photon per Geant4 event, therefore we have a maximum of one PMT triggered and can use the ‘pmtHitID (in the code)’ information for each event. This gives us directly the ID of the PMT which allows us to use the corresponding QE and check if the PMT is excluded from analysis. A PMT hit is recorded each time when a photon is registered in the PMT photocathode (100)

\[
LCE(x,y,z) = \frac{\sum_{\text{events inside TPC}} \text{PMTHits}_n \cdot QE(PMTID)_n \cdot CE \cdot QE_{increase}}{\sum_{\text{events inside TPC}} \text{photons}_\text{generated}(x,y,z)}
\]
3.3. relative Light Collection Efficiency $rLCE$

The $rLCE$ is defined as the LCE relative to its mean value and can be obtained for MC and real data:

$$rLCE_{MC}(x,y,z) = \frac{LCE(x,y,z)}{LCE\text{mean}}$$ (5)

$$rLCE_{data}(x,y,z) = \frac{ly(x,y,z)}{ly\text{mean}}$$ (6)

3.4. Light Yield $LY$

TPC can also be described by a light performance. To perform this three-dimensional light performance calculation, which others can verify the small-scale symmetry of different detector volumes, the detector is divided into 1000 volumes, 10 volumes in each direction. The light yield in each of these volumes can be obtained by the following equation 7:

The $LY$ of the MC simulation can be assumed as (for average photon yield from NEST ($W = 50ph/keV$, at 32 keV, at 150 V/cm)):

$$ly(x,y,z) = \frac{1}{W} \cdot LCE(x,y,z)$$ (7)

$\frac{1}{W}$: Average energy that is required to produce one scintillation photon.

4. Results

The final simulation of the dual phase TPC of argon shows in the figure 3. Where the particle incident is optical photon because is the easiest way to see the incoming particles and the signal detected by PMT. The simulation was done in Geant4 [1], which is a toolkit for the simulation of the passage of particles through matter.

Figure 3: Left: TPC Simulated in Geant4 with the distribution of detected photons. The photons are stopped by the reflection mechanisms and the electric field. Right: 1 GeV muon beam interaction and the detector response. Primary beam (blue line), interactions (red points and lines), photons produced (green lines).

For the initial analysis of the dual phase TPC and photomultipliers, optical photon events were generated, since they interact easily with the argon leaving a trace as in the figure 3. Signal
produced inside S1 and S2 are detected by PMTs (BOTTOM and TOP respectively) figure 4 which in turn are detected with photomultipliers. As has been pointed out, there is an charge amplification and more events are detected in S2 than S1. However, it will depend on beam position.

![Figure 4: Events detected in the TPC (sight on the axis x e y) S2 region.](image)

According to our source code, the events generated for the efficient collection of photons in the photomultipliers must take into account the QE and CEs. The figure 5 shows a greater interaction in the Bottom PMTs than top PMTs.

![Figure 5: LCE $R^2$ y z (radius vs height). Left: LCE BOTTOM PMTs. right: LCE in BOTTOM PMTs.](image)

One can point out, the bigger radius TPC has, the lowest photoelectron will be produced. Besides, the LCE is 4.5%.

On the other hand, the respective graphics for the LY 6, Bottom and top PMT in the area vs z axis
Finally, the dual phase TPC was proved with muon in order to obtain a signal of muon neutrino. It is well worth remembering that neutrino-argon produce muons and pions given by:

\[
\nu_\mu + Ar \rightarrow \mu^- + \pi^+ + Ar \\
\bar{\nu}_\mu + Ar \rightarrow \mu^+ + \pi^- + Ar
\]

Muons and pions are charged particle and they interact with argon. Starting from this one can reconstruct the interaction vertex in the TPC.
As can be seen in the figure 7, ionization and scintillation take place, these are detected by the PMTs. Also, positive muons are detected ($\mu^+$).

5. Conclusions
With this Monte Carlo-based simulation package is possible to study the effects, phenomena and parameters of the dual phase TPC of argon that are necessary for a complete understanding of the detector. After some basic tests, which verified the geometric implementation of the simulated configuration of the detector, as well as the physics implemented, the simulation package was used to characterize the TPC with calibration simulations.

In a first stage, light collection efficiency was obtained, $10^6$ optical photons were simulated in the liquid argon volume of the TPC and the number of collisions detected in the PMT was determined, with LCE of 4.5% in PMTs.

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