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Numerical Studies on Primary Ionization in TPC

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Abstract. Identification followed by directionality measurement using reconstruction of tracks is very crucial for studying the reaction vertex kinematics. In the field of low-energy nuclear physics, Active-Target Time Projection Chambers (AT-TPCs) can be used to study the nuclear reaction kinematics through tracking of the reaction products which is important for cross- section measurement. Ions produced in primary ionization by any charged particle along their track in the active gas volume of TPC can be utilized for track reconstruction with position- sensitive electron collection system placed inside an electric field. The TPC gas volume acts as the tracker of the reaction products and the target for the reaction with the incoming projectile simultaneously which is advantageous to conventional detector arrays. In this context, the design of the electric field in the drift volume of the TPC is an important criterion for precise tracking as the tracking capability of the TPC is strongly governed by the homogeneity of the electric field. Due to the lesser mobility of positive ions produced in primary ionization, their accumulation in the drift volume can distort the local electric field. In low-energy nuclear physics, this effect may be substantial due to the significant amount of ionization produced by the low-energy projectile and reaction products. Here we report the spatial information of primary space charges produced by cosmic muon and alpha particle obtained with geant4 [1] and Heed [2] simulation packages. We have used photo absorption and ionization physics lists in geant4 for the simulation and compared the results with that of the Heed. The simulation results for the change in pressure of gas volume will be reported. These results can be used for finding the distortion of the electric field due to the space charge in the drift region of the TPC which can be helpful for designing an AT-TPC for low-energy nuclear reaction experiments.

1. Introduction

In Nuclear Astrophysics, two main areas of interest are to understand the energy generation in stars and the relative abundance of the elements and their isotopes [3]. To understand these phenomena, the nuclear reaction cross-section of light nuclei at stellar thermal energies is an important observable to measure experimentally. Time Projection Chamber (TPC) [4], a gas-filled detection volume in an electric field used for three-dimensional tracking of charged particles to determine their energy and identification. On passing through the gas filled-detector, a particle will produce primary ionization along its track and the ionization electrons drift towards the anode where two-dimensional position information is collected. The three-dimensional image of the track is formed by measuring the drift time of the primary electrons. This device can be made useful to study low-energy nuclear reactions and measure the reaction cross-section. In an Active-Target TPC (AT-TPC) [5], the filling gas of the TPC acts as the target of the nuclear reaction which turns out advantageous in comparison to the conventional use of a fixed target. It allows almost 4π efficiency in particle detection due to its geometry. Therefore, tracking of the projectile as well as the reaction products with AT-TPC can lead to an efficient reconstruction of nuclear reaction kinematics.

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The tracking capability of the TPC is crucially dependent on the homogeneity of the drift field. However, the production of space charge inside the TPC can often result in distortion of the local electric field. In high energy experiments, the ions drifting back from the multiplication region (known as Ion Back Flow) to the drift volume, can cause such a distortion. A charged particle loses mean energy per unit path length which is described by the Bethe-Bloch equation [6]:

$$-\frac{dE}{dx} = 2\pi N_a r_e^2 c^2 \rho \frac{Z}{A}\frac{q^2}{\beta^2}\left[\ln\left(\frac{2m_e\gamma^2 v^2 W_m ax}{I^2}\right) - 2\beta^2 - \delta - 2\frac{C}{Z}\right] \quad (1)$$

where the following symbols have been used:

- E energy of the traversing particle,
- Na Avogadro's number,
- re classical electron radius,
- c speed of light in vacuum,
- me electron mass,
- I mean excitation potential,
- Z atomic number of absorbing materials,
- A atomic weight of absorbing material,
- r density of absorbing material,
- q charge of incident particle,
- $\gamma = \frac{1}{\sqrt{1-\beta^2}}$, Lorentz factor,
- v/c of the incident particle,
- W_{max} maximum energy transfer in a single collision,
- d density correction,
- C shell correction.

In the case of low energy nuclear physics experiments, the projectile can accumulate substantial space charge in the drift volume itself due to primary ionization being proportional to the square of the charge of the beam particle. For this reason, lower atmospheric pressure is suitable for nuclear reactions in gaseous detectors. In this work, we present the numerical study of the primary ionization as an effect of different sub-atmospheric pressure in TPC. Details of the numerical methodologies are given in the next section.

2. Simulation Framework

As discussed in the previous section production of space charge along with the primary ionization affects the uniformity of the drift field of the TPC. We have simulated the electric field inside the drift volume and generated primary ionization from both high and low energy charged particles. Cartesian coordinate system has been used for our study. Our goal is to find the amount of ionization deposited in the sensitive volume by 1 GeV muon shot horizontally along the Z-axis of a detector simulation consisting of a cylinder of the above-mentioned volume which is shown in figure 1.

2.1. Electric Field

The electric field in a given TPC geometry was simulated using a Finite Element Method (FEM) package, namely the COMSOL Multiphysics [7]. The cylindrical gas volume of the TPC has 80 cm height and a diameter of 25 cm. The origin of the coordinate system is at middle of the gas volume. A voltage of -15000 V has been given to the top plate of the field cage of the TPC which comprises 39 equi-spaced copper rings. The rings are connected through resistors so that the voltage drop is applied

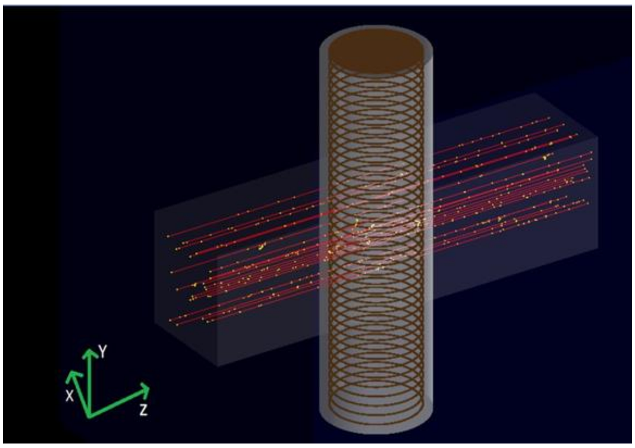

Figure 1. TPC geometry in Geant4 interface

between alternate ring. The calculation has shown that along the axis (y-coordinate) of TPC, the norm of electric field is almost uniform with a magnitude of 186 V/cm, as shown in figure 2.

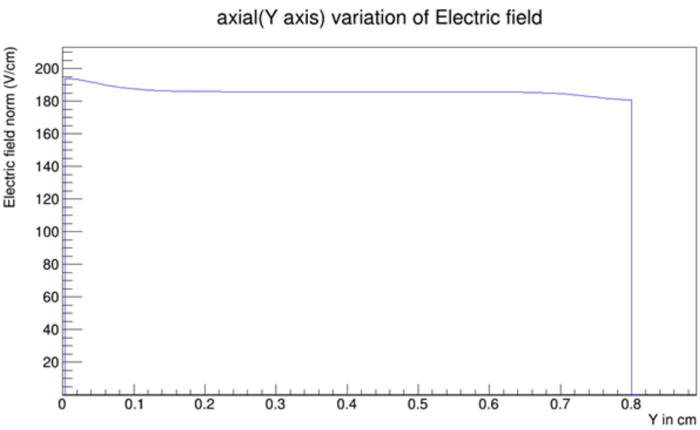

Figure 2. TPC axial electric field

Variation of electric field along radial (z-coordinate) direction and the radial axis of a ring electrode, 10 μm from the upper surface from it and between two ring electrodes are shown in figure 3.

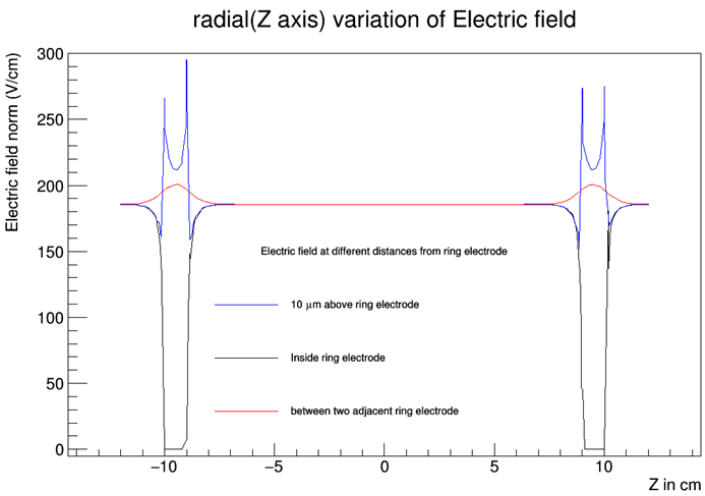

Figure 3. TPC radial electric field

2.2. Primary Ionization

The particles generation and tracking in geant4 were governed by low energy physics lists Livermore, Penelope, and PAI in simulation. A gas mixture of argon and carbon-di-oxide 70:30 has been considered. The HEED++ package has also been used to calculate the primary ionization caused for comparison with Geant4 results.

Primary ionization distribution along Z in centimeter which is the radial direction of TPC has been shown in the figure 1. We shot 1000, 1 GeV muon from z=-12.5 cm along the radial (z coordinate) direction. The number of primary electrons from HEED++ and geant4 generated the muon in the TPC is shown in figure 4.

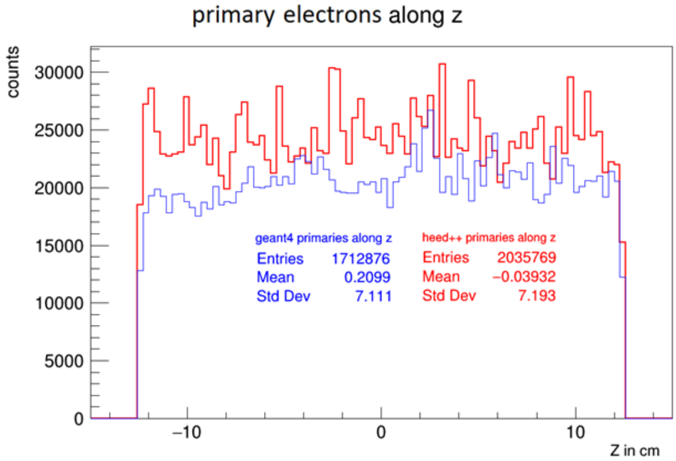

Figure 4. Position distribution of Primary ionization by μ−

The primary electrons produced per event per cm in geant4 is roughly 68 (1712 in 25 cm) which is quite comparable to the result from HEED++ which is 81 (2035 in 25 cm) per event per cm shown in 5. Therefore, our model in Geant4 estimates number of primary electron almost 15% less than Heed++ results which is not substantial.

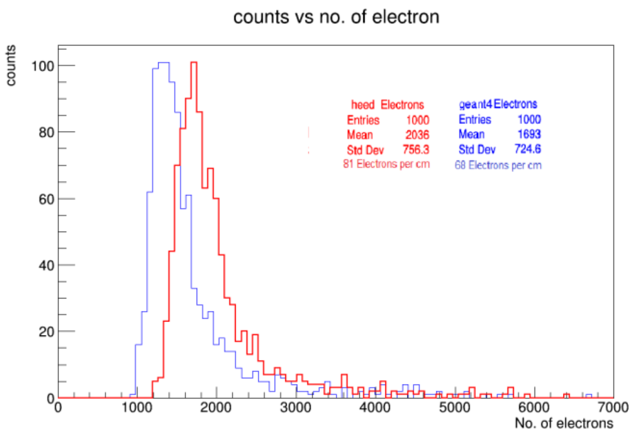

Figure 5. number of Primary ionization distribution of μ^-

This study on the primary ionization by a 1 GeV muon is to verify our model in geant4 and compare the results with HEED++. The study of primary ionization with our geant4 model for alpha in wide range of gas pressure which is lower than atmospheric pressure has been discussed in the next section.

3. Primary Ionization for wide range of pressure

We only use geant4 to simulate primary ionization by alpha in both atmospheric and sub- atmospheric pressure. Low energy nuclear projectile such as alpha in atmospheric pressure (760 Torr) can accumulate very high space charge while propagation as shown in figure 6. We have found 33684 number of primary electrons produced per event per cm from 5.6 MeV alpha shot in the earlier mentioned TPC volume in the radial direction. This huge ionization reduced the range of the projectile substantially. We have used the ideal gas model in our TPC for low pressure. Simulation of primary ionization governed by basic thermodynamic equations mentioned below, gas density is linearly proportional to the pressure.

$$PV = nRT \tag{2}$$

$$\rho = \frac{mP}{RT} \tag{3}$$

Where m is mass of a gas molecule, ρ is density, P is pressure, T is temperature and V is volume of the gas. We have shown results of primary ionization distribution by 5.6 MeV alpha along the radial direction (Z in cm) of TPC for 10%, 30%, 50%, 70%, 90% and 100% of atmospheric pressure which is shown in figure 6. Total number of electrons changes from 2720 at 10% of atmospheric pressure (76 Torr) to 33600 at atmospheric pressure (760 Torr) which is linear with pressure shown in 7.

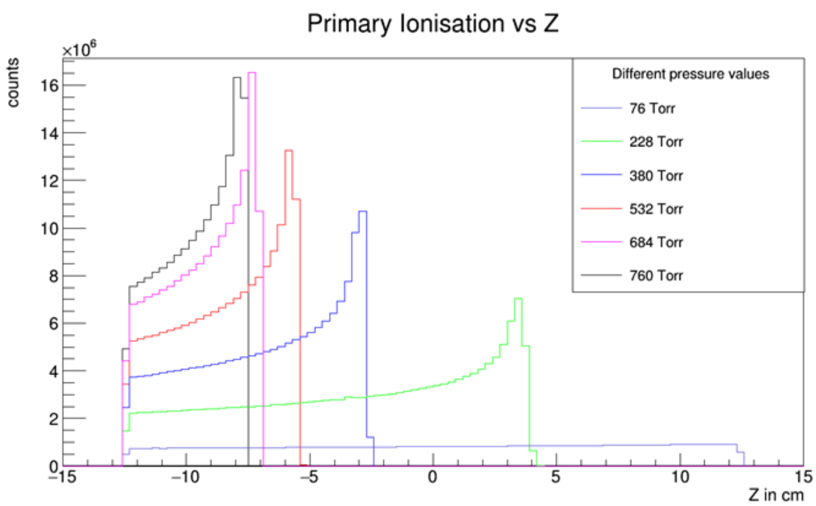

Figure 6. Primary ionization distribution by alpha for different range of pressure

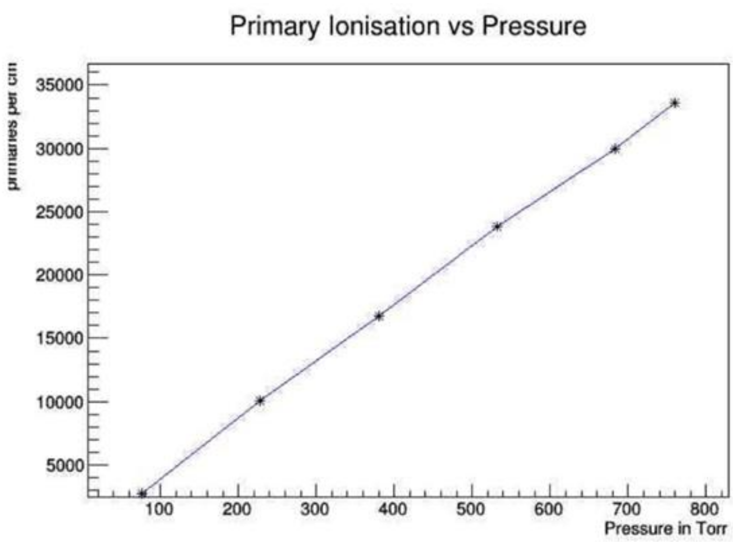

Figure 7. Primary ionization by alpha for different range of pressure

4. Concluding remarks

From the above study, we can conclude that for cylindrical TPC of 25 cm diameter, 10% to 30% of atmospheric pressure is required have a track that can cover the detector at the end of the TPC. With decreasing pressure number of the gas molecule will also decrease. Hence the number of primary ionizations per unit length also decreases significantly. In future, we will study the distortion of the drift field by using the space charge density by the above-mentioned primary ionization position information.

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