Primary Ionization Simulation for Different Gas Mixtures

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Abstract. The primary ionization in a gas mixture is crucial in nuclear and particle physics experiments. In many particle physics experiments, the primary ionization is utilized in understanding the charge density and discharge formation studies. We present the simulation of primary ionization in argon based gas mixtures to get the number of primaries, energy and spatial information with geant4 and heed++ toolkits that have been used to simulate the passage of particles through the matter. The geant4 toolkit has an advantage of obtaining the particle information like energy deposition and position co-ordinates after each step i.e., at which the particle has done some interactions in a complex, realistic, three-dimensional geometry. These steps generate each interactions after computing the cross-sections of physics processes that were taken into account for this simulation in a gas volume. The number of primaries generated with the geant4 toolkit were also compared with those obtained using heed++. Alpha and muons were simulated to study the primary ionization. A similar study of primary ionization was carried out with ^{55}Fe which is radioactive in nature and captures electron. ^{55}Mn (X-rays), νe, auger electrons and gammas were produced in this process. Gamma simulation has also been carried out. The responses of alpha, muon, ^{55}Fe and gamma in the argon based gas mixtures were found to be distinct due to their different properties.

Keywords: Primary ionization, geant4, heed++, argon based gas mixtures, alpha, muon, ^{55}Fe, gamma.

1. Introduction

The gaseous ionization detectors [1] have been utilized in many particle physics experiments like CMS [2, 3], LHCb [4], INO [5] and in the upgraded ALICE-TPC [6]. The motivation of the current work is to study the primary ionization produced by particles from various sources in different argon based gas mixtures. The primary ionization when produced initiates the transport and amplification of electrons and ions in the detector. Thus, it is important to understand the different processes to interpret and predict the response of any gaseous ionization detector. In high rate experiments, for the long-term operation of the detectors the aging resistance, radiation hardness and stability against discharges need to be understood. Irreversible damages such as enhanced leakage currents, a permanent short between the electrodes of the detector are caused by the discharges that may render the detector non-operational. Also, it has been proposed that charge density in the amplification region could lead to discharge and disturb the stability of the detector. Primary ionization simulated using geant4 [7] with an alpha source radiating into an argon gas mixture has already been reported in [8, 9]. Apart from alpha simulation [8] we present here the simulation of primary ionization in argon based gas mixtures using muon and ^{55}Fe to get the number of primaries, energy and spatial information. Additionally heed++ simulation has been presented here. The numerical model, results and conclusions are presented in following sections.

2. Numerical Model

The geant4 and heed++ [10] toolkits were used in order to simulate the primary ionization in different gas mixtures with alpha, muon and ^{55}Fe sources. Geant4 is a toolkit for the simulation of the passage of particles through the matter. It has applications in particle and nuclear physics, accelerator physics, medical and space sciences. It is possible to simulate the radiation source, target and the detectors for a given experiment in geant4. A particle undergoes interactions, decays, scatterings after each step due to the different physics processes used for the simulation, chosen as per the experiment. Thus cross-sections are calculated as per the physics processes. Then the simulated data is analysed and utilized for the conclusions. Similarly we can simulate particle detectors in garfield++ [11] which is a toolkit for the measurement of ionization in gaseous or semiconductor detectors. The ionization pattern produced along the track of the particles can further be simulated using the heed++ program that can be invoked from garfield++. Thus the generation and study of primary ionization has been done using geant4 and heed++.

2.1. Generation of Primaries

Different gas mixtures have been used such as Ar−CO_2 (90-10), Ar−CO_2 (80-20), Ar−CO_2 (70-30), Ar-CO_2-CF_4 (45-15-40). Argon gas acts as a target for ionization, CO_2 acts like a photon quencher and CF_4 is an electron quencher. Argon has higher ionization energy so gets excited easily as compared to CO_2 gas. Photons are released when an excited argon atom gets de-excited. Further the de-excitation of the argon atom ionises CO_2 via photo absorption. An alpha beam (^{241}Am) of 5.6 MeV energy placed at the middle of the gas volume was shot as per the experimental set-up [8, 9]. The three-dimensional active gas volume had dimensions of 5 cm along x and y, and 20 cm along z direction. Physics lists such as, EMLivermore, EMPenelope, Photo Absorption Ionization (PAI), PAI-Photon were used to simulate the particles in the gas volume [8]. Only 10,000 events were shot in the volume of gas. In another analysis for the simulation of 1 GeV muons, the same dimensions of the gas volume, physics lists and 10,000 events were chosen and shot from x=0, y=0, z=-10 cm position in the Ar−CO_2 (70-30) gas mixture. In another simulation, a radioactive source ^{55}Fe of 5.89 keV energy placed at the middle of the gas volume was simulated using Ar−CO_2 (70-30) gas mixture. The dimensions of the gas volume and number of events were chosen to be the same as used in alpha source. G4AtomicDeexcitation was chosen as the physics list. ^{55}Fe captures the electron, let us assume, from K-shell thereby creating a vacancy that gets filled by L-shell emitting ^{55}Mn ($K_{\alpha1}$) (X-rays). If M-shell fills the vacancy of the K-shell then ^{55}Mn ($K_{\beta1}$) are emitted. Sometimes the photons that gets released eject the outer electron and this process is known as *auger electron emission*. So the photons emitted by X-rays ($K_{\alpha1}$) get utilized to overcome the auger electron binding energy, kinetic energy of auger electron and photons also get released in the process. Many auger electrons then produce the auger cascade. Since it is electron capture so a neutrino is also emitted. Thus the electron capture reaction is given by:

$$^{55}\text{Fe} \xrightarrow{\text{e-capture}} {^{55}\text{Mn}} + e^- + \nu_e + \gamma \quad (1)$$

Figure 1 show the geant4 display of the simulated volume. The blue and yellow coloured volume was filled with one particular type of gas mixture and the source was placed along the z-direction to interact with the gas mixture. The corresponding results have been presented in section 3.

3. Results

The simulation process was carried out for the three different sources alpha, muon and ^{55}Fe in different gas mixtures using geant4 and heed++. We describe them in the next sub-sections.

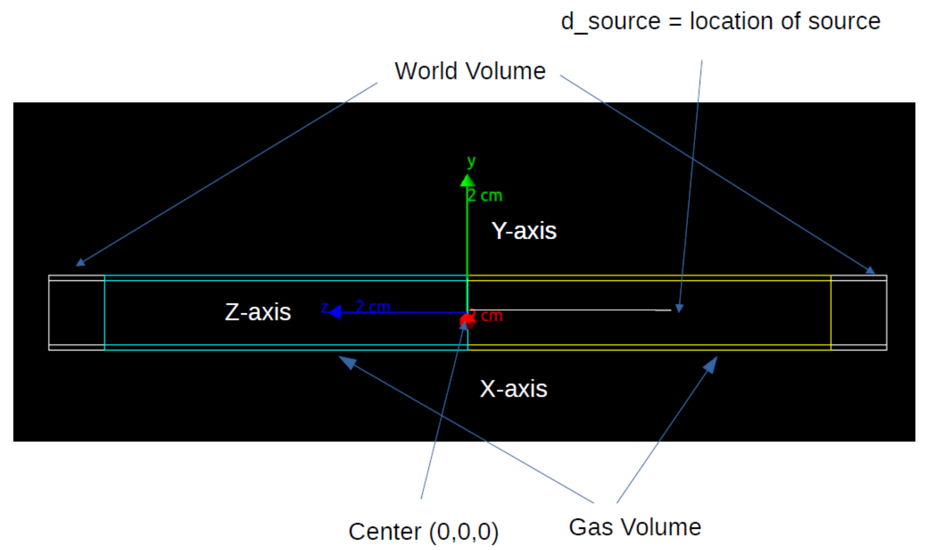

Figure 1. The geant4 display of simulated gas volume and the location of source.

3.1. Alpha Simulation

The alpha simulation was done to extract the information about the primaries and then transportation and amplification were done to obtain discharge probability in single and triple GEM detectors [8]. Here we show the information of primaries. Figure 2 and 3 shows the x and y co-ordinates of the primaries obtained when ^{241}Am (alpha of 5.6 MeV energy) placed at middle of the gas volume was simulated using four gas mixtures; Ar−CO_2 (90-10), Ar−CO_2 (80-20), Ar−CO_2 (70-30) and Ar-CO_2 -CF_4 (45-15-40) and the colours in the plots are green, blue, red and pink respectively. The colouring scheme is the same for figures 2 - 5. Since argon gets easily ionized due to the higher ionization energy than CO_2 so increasing the argon ratio increases the ionization too. Therefore, Ar−CO_2 (90-10) gas mixture produced more counts as compared to the other gas mixtures. Both figure 2 and 3 shows that x and y co-ordinates have gaussian distribution as the number of events are large, centered at zero as the particles were shot at x=y=0.

Figure 4 shows the z co-ordinates of the primaries from ^{241}Am (alpha) simulated in the four argon based gas mixtures. As the particle travels along z direction in the gas mixture, it gets ionized and form primaries. When the argon ratio was increased the number of primaries also increased. In figure 4, the z coordinate indicates the range. It may be noted that the smallest range was observed for Ar-CO_2-CF_4 (45-15-40) gas mixture since the argon percentage was 45% only. The range of alpha in these gas mixtures lie between 3.3 - 5.4 cm. Figure 5 shows the Bragg curves obtained from simulation of ^{241}Am (alpha) using geant4 toolkit for the different argon based gas mixtures. The Bragg curve is the energy loss rate as a function of the distance through a stopping medium. The particle deposits energy constantly along its track but at the end of the trajectory it is maximum. This is because the energy varies inverse of the square of the velocity, so there is an increase in the interaction cross section as the charged particle's energy decreases. Thus before coming to the stop a particle deposits most of its energy.

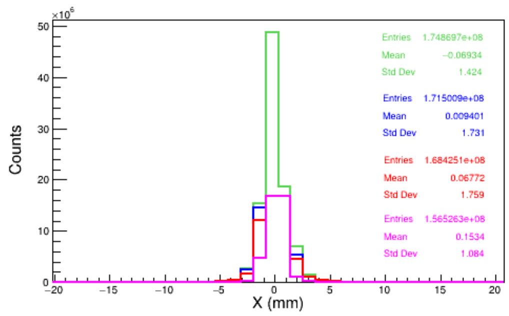

Figure 2. The x co-ordinates of the primaries obtained from simulation of ^{241}Am (alpha of 5.6 MeV) using four different argon based gas mixtures.

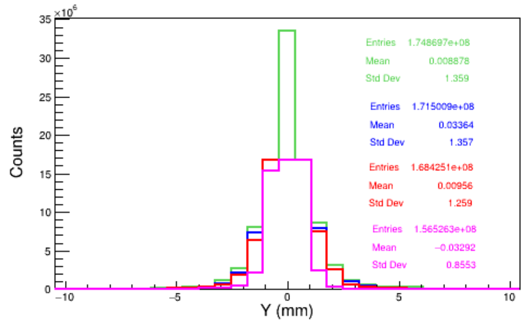

Figure 3. The y co-ordinates of the primaries obtained from simulation of ^{241}Am (alpha of 5.6 MeV) using four different argon based gas mixtures.

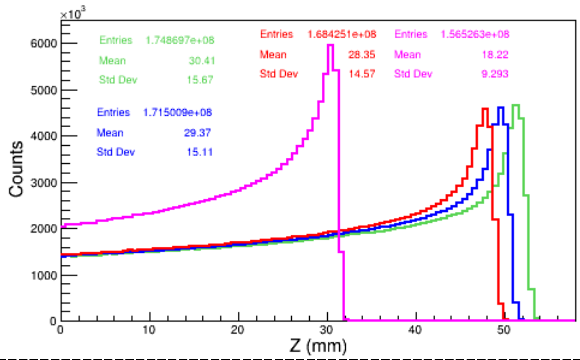

Figure 4. The z co-ordinates of the primaries obtained from simulation of ^{241}Am (alpha of 5.6 MeV) using four different argon based gas mixtures.

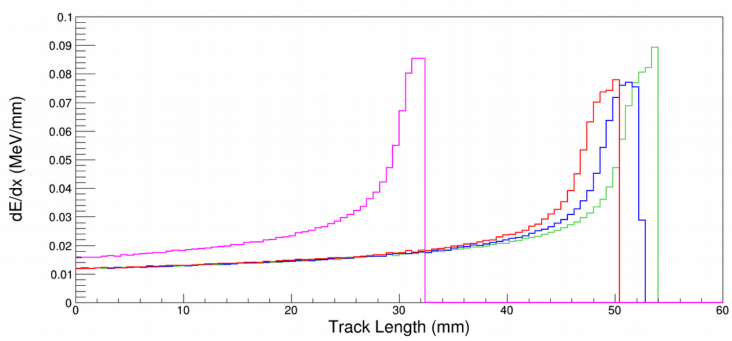

Figure 5. The Bragg curves obtained from simulation of ^{241}Am (alpha of 5.6 MeV) using four different argon based gas mixtures.

Figure 6 shows the position co-ordinates and number of electrons respectively when ^{241}Am (alpha of 5.6 MeV) placed at middle of the gas volume was simulated using Ar-CO_2 (70-30) gas mixture. Only 10,000 events were shot using heed++. The x and y co-ordinate demonstrates the gaussian distribution whereas the z co-ordinate represents the range i.e. 4.21 cm which matches with the standard results [12]. The number of electrons obtained from geant4 and heed++ are 1.68 X 10^5 and 1.88 X 10^5 respectively. A slight difference in the number of electrons is due to the fact that in heed++ number of electrons are calculated from the ratio of energy of the alpha beam by the effective ionization potential of the gas mixture, whereas in geant4 the alpha interacts with gas mixture after each step as per the physics process.

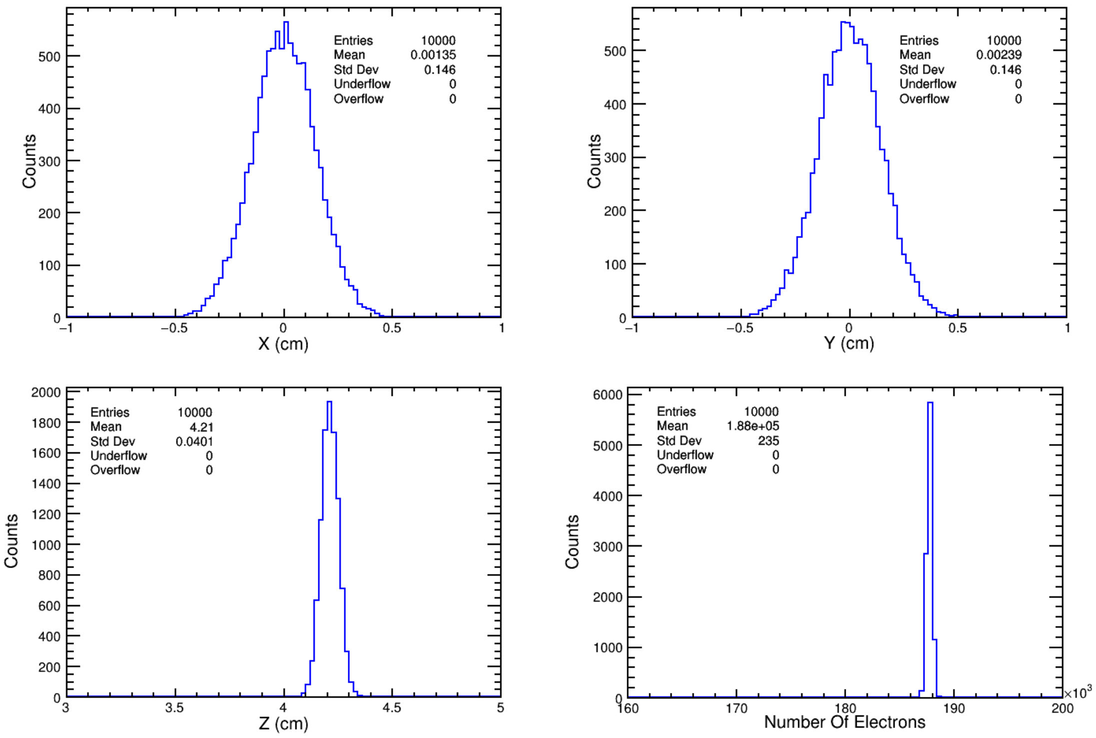

Figure 6. The x, y and z co-ordinates and number of electrons respectively obtained from simulation of ^{241}Am (alpha of 5.6 MeV) in Ar-CO_2 (70-30) gas mixture.

3.2. Muon Simulation

Figure 7 shows the position co-ordinates and number of electrons obtained when muon of 1 GeV placed at x=0, y=0, z=-10 cm was simulated in Ar-CO_2 (70-30) gas mixture. The figure show that x and y co-ordinates have a gaussian distribution. Since muons have a large range so the z co-ordinate represent a uniform distribution. We also simulated the muons using heed++ with the same inputs as used in geant4. The number of primaries/cm obtained from geant4 and heed++ were 64.85 and 40 respectively.

3.3. ^{55}Fe Simulation

Figure 8 shows the x, y, z co-ordinates of the primaries obtained when a radioactive source (^{55}Fe of 5.89 keV energy) placed at middle of the gas volume was simulated in Ar-CO_2 (70-30) gas mixture. The x and y distributions are gaussian. The counts decrease when primaries travel along its track due to the loss of energy as shown by the z co-ordinate. The zoomed view of the auger cascade is also shown in this figure. These electrons were formed when the photons knocked the electrons from the outer shell.

3.3.1 Gamma Simulation

10,000 events of gamma were also simulated using heed++ in Ar-CO_2 (70-30) gas mixture with the same dimensions of the gas volume as used in section 3.1. Figure 9 shows the number of electrons obtained were 196 when gamma placed at (0,0,0) was simulated in Ar-CO_2 (70-30) gas mixture using heed++. The products obtained from gamma simulation are same as obtained from ^{55}Fe simulation. Therefore gamma simulation has been an additional information to ^{55}Fe simulation. Figure 10 shows ^{55}Mn energy peaks of 5.89 and 6.49 keV obtained when gamma placed at (0,0,0) was simulated in Ar-CO_2 (70-30) gas mixture. These energy peaks exactly match with the standard results [13].

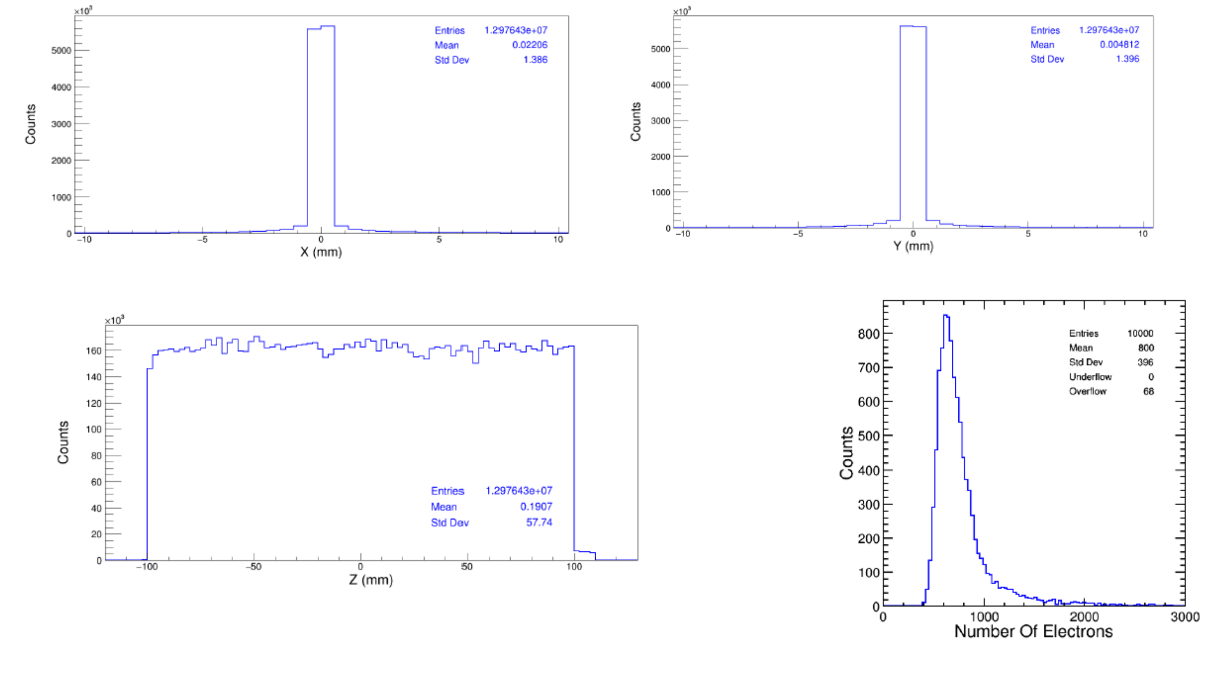

Figure 7. The x, y, z co-ordinates of the primaries and number of electrons respectively obtained from simulation of muon (1 GeV) placed at x=0, y=0, z=-10 cm in Ar-CO_2 (70-30) gas mixture.

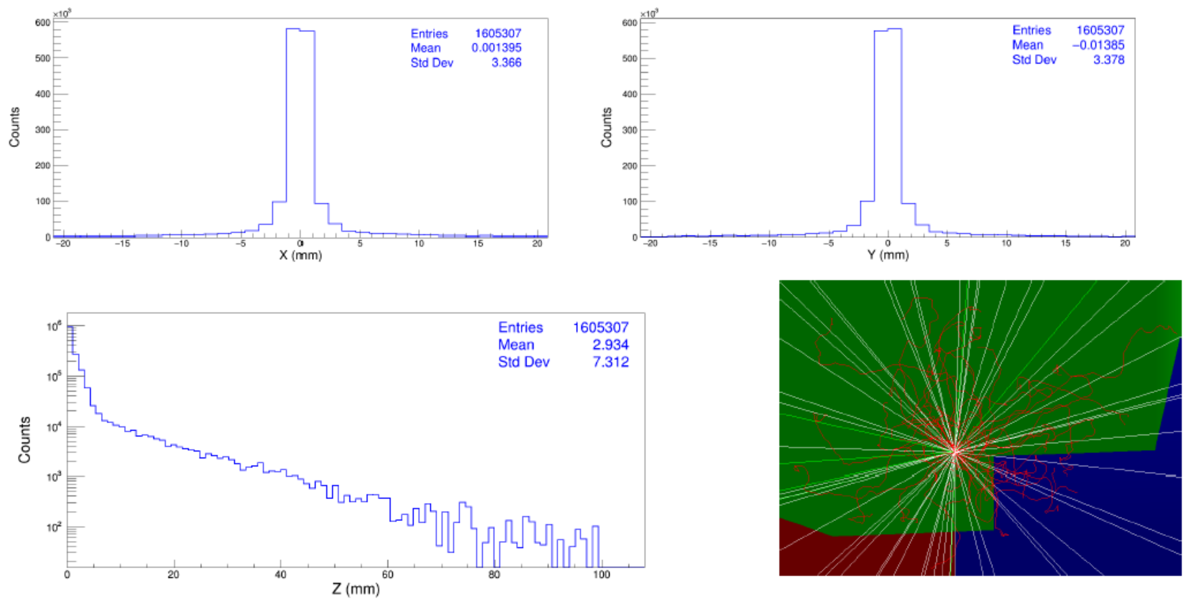

Figure 8. The x, y, z co-ordinates of the primaries respectively obtained from simulation of ^{55}Fe (5.89 keV) in Ar-CO_2 (70-30) gas mixture and a zoomed view of the auger cascade.

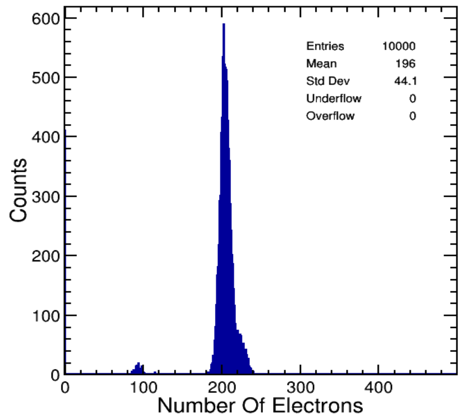

Figure 9. The number of electrons obtained from simulation of gamma source in Ar-CO_2 (70-30) gas mixture using heed++.

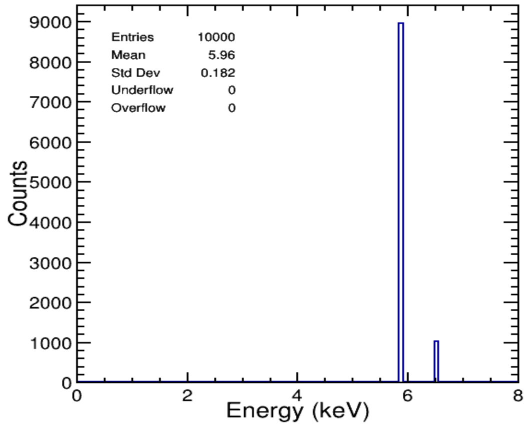

Figure 10. Energy peaks of ^{55}Mn of 5.89 and 6.49 keV respectively obtained from simulation of gamma source in Ar-CO_2 (70-30) gas mixture using heed++.

4. Conclusions

Thorough knowledge about primary ionization is necessary in nuclear and particle physics experiments as the primary ionization is utilized in charge density and discharge formation studies. So we simulated the alpha, muon, ^{55}Fe and gamma sources in different argon based gas mixtures to detect their response. Different responses were observed due to different properties of these sources. The geant4 and heed++ toolkits were utilized for the studies to obtain spatial information, number of primaries and Bragg curve for alpha particles, shot in argon based gas mixtures. The number of primaries obtained from alpha simulation using geant4 and heed++ were comparable. A similar simulation was done with muon source, shot in the Ar-CO_2 gas mixture to obtain the spatial information and the number of primaries. In another analysis, a radioactive source ^{55}Fe was simulated. ^{55}Fe captures the electron so the re-arrangement of electron takes place in the inner shells while emitting the x-rays. The obtained energy peaks of x-rays closely matched with the standard results.

5. References

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