Monte Carlo simulations of Microdosimetry for Space Research at FAIR

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Abstract. The exposure to high charge and energy (HZE) particles is one of major concerns for humans during their missions in space. As radiation effects essentially depend on charge, mass and energy of cosmic-ray particles, the radiation quality has to be investigated, e.g. by means of microdosimetry measurements on the board of a spacecraft. We benchmark the electromagnetic models of the Geant4 toolkit with microdosimetry data obtained with a walled Tissue Equivalent Proportional Counter (TEPC) with beams of HZE particles. Our MCHIT model is able to reproduce in general the response functions and microdosimetry variables for nuclear beams from He to Fe with energies of 80–400 MeV per nucleon.

1. Introduction

Future plans of space exploration include the construction of a station on the Moon and traveling to Mars [1]. One of the most important issues related to such projects is the health hazard to astronauts caused by exposure to radiation in space. Several research programs are in progress to investigate the physical and biological effects of space radiation and develop mitigating strategies to reduce risk to humans [2].

The radiation environment in deep space (far from the magnetic field of the Earth) is usually classified in two components: the solar particle events (SPE) and the galactic cosmic rays (GCR). The first component mainly consists of protons emitted by the Sun. Strategies to mitigate its effects include the use of proper shielding or the schedule of missions during phases of low solar activity [3]. However, the shielding from GCR represented by various nuclei from hydrogen to iron is much less effective because of their energy spectra extending to high energies. High-charge ($Z$) and energy ($E$) nuclei from GCR, known as HZE particles, can not be stopped by any shielding available in space missions. The maximum of the spectrum for specific GCR nuclei is between 100$A$ and 1000$A$ MeV. The fluxes of 10$A$ GeV nuclei is just two orders of magnitude lower [3]. Even though the fluxes of heavy nuclei (e.g. Fe) are much lower than the flux of protons or helium nuclei, the energy deposition of the former escalates with the square of the nuclear charge. As a result, the physical dose from GCR HZE particles is comparable to one from GCR protons. As soon as the biological effectiveness of each particle is considered, the
dose equivalent delivered by iron nuclei, for example, becomes even higher than by protons [4]. Therefore, the radiation effects due to HZE particles must be thoroughly investigated.

The experiments which investigated radiation effects in space have employed several types of detectors on the board of the Space Shuttle [5] and at the International Space Station [6]. Due to its compact size the Tissue Equivalent Proportional Counter (TEPC) [7] is frequently employed for microdosimetry measurements in space. Such kind of detectors has also been used in ground-based experiments with HZE particles from accelerators to model irradiation in space. TEPC usually consists of a gas cavity surrounded by a plastic shell made of a tissue equivalent material. The response function of the detector gives the probability distribution of lineal energy, $y$, which is defined as the energy imparted by particle to the sensitive volume divided by the mean chord length of the cavity.

Future studies for space exploration shall continue to use TEPCs following the recommendations of the National Council on Radiation Protection and Measurements (NCRP) [8]. Several experiments at HIMAC in Japan and AGS in the USA used TEPC detectors for microdosimetry measurements of HZE particles in the energy range of 200 A to 1000 A MeV [9–11]. Similar measurements, but with heavy nuclei at higher energies are expected to be performed at the BIOMAT facility at FAIR [12]. These experiments will contribute to a better understanding of radiation effects induced by cosmic rays.

2. Simulations with MCHIT

A computational model which is able to simulate the propagation of energetic nuclei in extended media serves as a powerful tool in investigating radiation effects. In particular, the response function of a TEPC which represents the probability distribution of lineal energy can be estimated by the Monte Carlo method. The patterns of energy deposition around the track of a HZE particle can be also studied by Monte Carlo methods [13] in order to understand biological effects of GCR.

The Monte Carlo model for Heavy Ion Therapy (MCHIT) was developed at FIAS to study physics phenomena relevant to heavy-ion therapy of cancer [14]. MCHIT is based on Geant4 which is a rapidly developing toolkit for calculations in nuclear, particle, space and medical physics [15]. It comprises software libraries for detailed simulations of the particle propagation in various media. MCHIT describes a wide set of experimental data related to heavy-ion therapy. This includes depth-dose profiles for protons and carbon nuclei in tissue-like materials, yields of secondary nuclear fragments, energy spectra and angular distributions of secondary neutrons. It was also demonstrated [16] that MCHIT reproduces microdosimetry spectra measured by walled TEPCs for neutron and carbon beams.

In this work the MCHIT model is extended to describe microdosimetry data relevant to space research. The experimental data collected at HIMAC and AGS [9–11] are used to validate the model for calculations with beams of HZE particles. In these experiments a walled TEPC detector was irradiated by ions with energies from 200 A to 1000 A MeV. Detectors upstream and downstream of the TEPC were used to measure the impact parameter of the incoming ion and select events only without beam fragmentation. Due to this selection, the response functions of the TEPC measured in these experiments are sensitive only to electromagnetic processes induced by beam nuclei in TEPC, as fragmentation events of beam nuclei are rejected.

In this work MCHIT is build with Geant4 of version 9.5 with patch 1. The electromagnetic processes are simulated by means of G4EmStandard_opt3 and G4EmPenelope [17] Physics Lists which contain sets of electromagnetic models. The Penelope models have a lower energy threshold of 250 eV for production of delta-electrons compared to the standard electromagnetic models (with a 990 eV threshold). Therefore, once the difference in results obtained with these two Physics Lists is found, this can indicate the importance of transporting of low-energy electrons.
The geometry of TEPC is represented in simulations by a cavity of 12.7 mm in diameter surrounded by a 2.54 mm thick plastic shell. No wires and electric potential inside the gas cavity are simulated. The gas pressure is set to the values used in experiments [9–11] for each ion beam corresponding to simulated tissue objects with diameter of 1 and 3 μm. A total of $2 \times 10^7$ primary ions are simulated for each beam energy. In each event the energy deposition inside the gas cavity and the impact parameter are scored to calculate the response function of the detector.

3. Results
The energy imparted to TEPC by 210A MeV $^{20}$Ne in central collisions with small impact parameters $b < 0.8$ mm is presented in Fig. 1. MCHIT successfully describes this distribution with both sets of electromagnetic models. Figure 2 demonstrates the mean energy deposition as a function of the impact parameter. MCHIT describes well the mean energy deposition at impact parameters smaller than the cavity radius (6.35 mm). At the interface between gas and plastic there is a bump in the mean energy deposition in the experimental data and simulation results. This phenomenon is due to the enhancement of production of delta electrons when a primary ion grazes the gas/wall interface. Such delta electrons enter the gas cavity and elevate the energy deposition in grazing collisions. Both Physics Lists describe this phenomenon well despite of different energy thresholds for production of delta electrons. One can conclude that delta electrons with kinetic energy below 990 eV do not affect simulation results. The green line presents the product of the linear energy transfer (LET) and the chord length at a given impact parameter. It deviates from the experimental results and MCHIT simulations due to the above-described enhancement of energy deposition in grazing collisions and also due the violation of the charged-particle equilibrium [9] for this detector.

![Figure 1](image1.png)  
**Figure 1.** Energy imparted to TEPC by 210A MeV neon ions at impact parameters $b < 0.8$ mm. Experimental data from [10].

![Figure 2](image2.png)  
**Figure 2.** Energy imparted to TEPC by 210A neon ions as a function of impact parameter. Experimental data from [10].

Calculations of the mean energy imparted to TEPC by 360A MeV $^{56}$Fe ions as a function of impact parameter with G4EmStandard_opt3 and G4EmPenelope provide again equivalent results with the lowest possible energy thresholds for delta electrons. Figure 3 presents simulation results only with G4EmStandard_opt3 but using various energy thresholds for production of delta electrons. We can see that calculations with the energy threshold of 100 keV can not reproduce the enhancement of energy in grazing collisions, while with the energy threshold of 10 keV this phenomenon is reproduced. The mean energy imparted to TEPC in events with
impact parameter smaller than 3 mm is overestimated with both models even with the lowest possible energy thresholds for delta electrons. This overestimation needs further investigations.

Figure 3. Energy imparted to TEPC by 360 A MeV iron ions as a function of impact parameter. Experimental data from [9].

Figure 4. Comparison of LET with $\bar{y}_D$ for iron ions of several beam energies. Experimental data from [9].

MCHIT results obtained with Penelope models for the frequency-average $\bar{y}_F$ and dose-average $\bar{y}_D$ lineal energy for several ions are listed in Table 1. The experimental values [10, 11] and results of the Monte Carlo code FLUKA [18] are shown for comparison. Calculations with Geant4 and FLUKA agree well the experimental values. Although TEPC does not measure Lineal Energy Transfer (LET) directly, $\bar{y}_D$ for heavier ions approximates LET, as already pointed out by Gersey et. al. [9]. This demonstrates the usefulness of TEPC data for estimating biological effects of radiation as several biological models describe such effects as a function of LET. The relation between LET and measured and calculated $\bar{y}_D$ is presented in Fig. 4 for iron ions with energy from 200 A to 1000 A MeV. A good agreement between simulations and data is found. $\bar{y}_D$ and LET agree well especially for high energy iron ions. Therefore, $\bar{y}_D$ can be used as an approximation of LET for iron ions.

4. Conclusions
Geant4/MCHIT describes well the TEPC response function as well as the microdosimetry parameters for a broad selection of ions and beam energies relevant for space research. Both electromagnetic Physics Lists G4EmStandard_opt3 and G4EmPenelope describe reasonably well the experimental data. MCHIT describes the wall effect due to the enhanced production of delta electrons inside the gas cavity when a primary ion grazes the wall/gas interface. The validation of MCHIT for space research should also include experiments which take into account fragmentation reactions for benchmarking of hadronic models. The inclusion of electromagnetic models for low energy processes from the Geant4-DNA project is foreseen as another extension. It will allow to study the patterns of energy deposition at few nanometers scale around the ion track.

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Table 1. Results for microdosimetry parameters $\tilde{y}_F$ and $\tilde{y}_D$ simulated with MCHIT. Experimental data from [10, 11]. Simulations results with FLUKA from [18].

| Ion   | Energy (A MeV) | LET (keV/μm) | $\tilde{y}_F$ (keV/μm) | $\tilde{y}_D$ (keV/μm) |
|-------|----------------|--------------|------------------------|------------------------|
|       |                |              | Exp. FLUKA              | MCHIT                  |
| $^4$He | 225            | 1.68         | 1.56                   | 1.67                   | 1.61                   | 2.58                  | 2.52                  | 2.41                  |
| $^{12}$C | 215   | 15.6         | 13.4                   | 14.41                  | 14.0                   | 16.1                  | 17.11                 | 16.4                  |
| $^{12}$C | 389   | 11.2         | 9.93                   | 10.2                   | 9.95                   | 12.4                  | 12.97                 | 12.2                  |
| $^{14}$N | 80    | 43           | 44                     | 43.8                   | 42.3                   | 47                    | 48.3                  | 46.0                  |
| $^{16}$O | 385   | 19.9         | 17.9                   | 17.54                  | 17.2                   | 20.8                  | 21.68                 | 20.8                  |
| $^{20}$Ne | 210  | 44           | 42                     | 43.5                   | 41.5                   | 48                    | 48.1                  | 45.4                  |
| $^{28}$Si | 375   | 61.9         | 50.4                   | 49.7                   | 49.0                   | 59.8                  | 65                    | 62.4                  |
| $^{28}$Si | 780   | 46           | 39                     | 41.6                   | 41.3                   | 47                    | 47.7                  | 46.4                  |
| $^{56}$Fe | 355   | 219          | 184                    | 186.4                  | 183                   | 224                   | 228.3                 | 220                  |

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