Radiation quality of cosmic ray nuclei studied with Geant4-based simulations

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Abstract. In future missions in deep space a spacecraft will be exposed to a non-negligible flux of high charge and energy (HZE) particles present in the galactic cosmic rays (GCR). One of the major concerns of manned missions is the impact on humans of complex radiation fields which result from the interactions of HZE particles with the spacecraft materials. The radiation quality of several ions representing GCR is investigated by calculating microdosimetry spectra. A Geant4-based Monte Carlo model for Heavy Ion Therapy (MCHIT) is used to simulate microdosimetry data for HZE particles in extended media where fragmentation reactions play a certain role. The effect of nuclear fragmentation on the relative biological effectiveness (RBE) of He, Li, C and Si in the energy range of 150–490 MeV/u. The effect of nuclear fragmentation on the relative biological effectiveness (RBE) of He, Li and C is estimated and found to be below 10%.

1. Introduction

Future space travels shall take humans to the Moon for extended periods and even beyond in interplanetary missions [1, 2]. Not only further technological developments will be necessary, but also a better understanding of the health risks to crew members exposed to galactic cosmic rays (GCR). The GCR spectrum is composed mainly by protons and helium nuclei with only a fraction of about 1% due to heavier ions showing a broad energy spectra peaked between 100–1000 MeV/u. Although the flux of high energy and charge (HZE) particles is low, a high biological effectiveness of such particles increases their contribution to the received biological dose. Since HZE particles can not be effectively shielded during the journey following chronic radiation effects are expected to be significant [3].

Shielding of crew members is indispensable for their protection from protons of solar particle events and from the proton component of GCR. However, the linear energy transfer (LET) of a HZE particle increases due to the energy loss in spacecraft materials, and a complex radiation field is created due to nuclear fragmentation reactions. Dose monitors for such radiation fields shall be able to cope with a broad LET spectrum. In particular, a Tissue Equivalent Proportional Counter (TEPC) has been applied for microdosimetry measurements aboard Space Shuttle [4]. TEPC emulates a micrometer volume of human tissue and measures lineal energy, y, of stochastic
events. Lineal energy is defined as the energy deposited to a sensitive volume of TEPC divided by its mean chord length [5]. The probability distributions of $y$ (microdosimetry spectra) measured by TEPC can be used in estimating LET and RBE of complex radiation fields [6, 7].

Our previous investigations of the response of TEPC to radiation fields relevant to space research [8] are extended to detailed simulations of microdosimetry spectra. In the present work such spectra resulting from irradiation of extended media with protons, helium and HZE particles in the energy range of 150–490 MeV/u are compared to experimental data. The contributions of secondary fragments created in fragmentation of beam nuclei are calculated. The FAIR facility will allow microdosimetry measurements and radiobiological experiments with HZE particles at higher energies. This will help to reduce the uncertainties in estimating the health risks of astronauts due to exposure to GCR.

2. Materials and Methods
The radiation environment inside a spacecraft due to GCR irradiation can be studied by Monte Carlo method. The interaction of GCR with various materials can be simulated with the Geant4 toolkit [9, 10]. Originally being developed for experiments in high-energy physics, the code is now widely used for modeling in space research. It comprises software libraries with a broad set of functionalities for the simulation and analysis of particle propagation in various media. A user should implement its own software application tailored to the particular research task.

The Monte Carlo model for Heavy Ion Therapy (MCHIT) is a Geant4-based application intended to study physics processes relevant to ion-beam cancer therapy [11, 12]. MCHIT has been used to describe a wide set of experimental data including 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. Microdosimetry spectra for neutrons, protons and light ions measured with TEPCs were also calculated [13, 14]. MCHIT is currently built with Geant4 of version 9.5 with patch 02. The electromagnetic processes are simulated by means of G4EmPenelope including models for ionization process of gas media by ions. The fast stage of nucleus-nucleus collision is modeled by Light Ion Binary Cascade model for helium and lithium projectiles and by Quantum Molecular Dynamics model for carbon and silicon projectiles. Further details on the physics list and respective models are given elsewhere [14].

In this study the MCHIT model is used for investigating the effect of nuclear fragmentation reactions on microdosimetry spectra and RBE for protons, helium and HZE particles. Microdosimetry spectra measured at NIRS, Japan for 160 MeV $^1$H, 150 MeV/u $^4$He and 490 MeV/u $^{28}$Si [15] as well as at GSI, Germany for 185 MeV/u $^7$Li and 300 MeV/u $^{12}$C [16] were taken for benchmarking. The measurements at NIRS were performed with a wall-less TEPC emulating a cylindrical tissue volume of 0.72 $\mu$m in diameter while at GSI a walled TEPC was applied emulating a spherical volume of 2.7 $\mu$m in diameter. At NIRS the wall-less TEPC was placed behind range shifters made of PMMA, while the walled TEPC was placed inside a water phantom at GSI.

RBE is estimated by MCHIT coupled with the Microdosimetric-Kinetic (MK) model developed by Hawkins [6] and extended by Kase et. al [7]. The impact of nuclear fragmentation reactions on the relative biological effectiveness (RBE) of radiation fields by helium, lithium and carbon at different water-equivalent depths is evaluated. Details of the calculational procedure can be found elsewhere [14].

3. Results and Discussions
Microdosimetry spectra were simulated for various ions showing a general agreement with experimental data as presented in figure 1. Panel (a) shows the spectrum for homogeneous proton irradiation of a wall-less TEPC behind a 163 mm-we (water-equivalent) range shifter. The spectrum is peaked at lineal energy $y = 1$ keV/$\mu$m extending up to 20 keV/$\mu$m. In panel
(b) the spectrum for helium beam with same wall-less TEPC but behind a range shifter of 157.1 mm-we is presented. In this case the spectrum is peaked at $\sim 15 \text{ keV}/\mu\text{m}$ due to primary ions while secondary protons give the main contribution for events below 2 keV/μm. Lineal energy events due to helium projectiles extend up to 200 keV/μm. Panels (c) and (d) show the spectra measured with a walled TEPC irradiated by a pencil-like lithium beam inside a water phantom at the plateau and Bragg peak of the depth-dose distribution, respectively. The disagreement between experimental data and simulation results in panel (c) is likely related to pile-up of events during data acquisition in experimental set-up as discussed elsewhere [14]. The change of radiation quality with depth in water is clearly seen. Not only the contribution of lithium changes due to the reduction of kinetic energy, but also the role played by secondary particles evolves. At the plateau position, the contribution of projectile-like helium fragments is seen between 0.2–18 keV/μm, and of target-like fragments between 18–100 keV/μm. This is explained by the fact that projectile-like fragments have velocities similar to the primary ion but smaller stopping power due to a smaller nuclear charge. The contribution of primary ions is peaked at 5 keV/μm and extends up to 22 keV/μm. When TEPC is moved deeper into phantom, the peak is shifted to $\sim 60 \text{ keV}/\mu\text{m}$ and a shoulder in the spectrum at lower $y$ values is clearly visible due to the contribution of helium and hydrogen fragments. Panels (e) and (f) show similar measurements with a pencil-like carbon beam at plateau and peak positions, respectively. Also in this case a clear change of radiation quality is observed with depth where a variety of secondary particles along with the primary carbon ions contribute to the spectra. The maxima are observed at 16 keV/μm and 120 keV/μm at plateau and peak, respectively. The underestimation of the satellite peak observed in the spectrum at the peak position indicates that the Geant4 models for nuclear fragmentation may need further improvements. The panels (g) and (h) present the spectra measured with the wall-less TEPC behind two range shifters of different thickness irradiated by silicon ions. As seen, the shape of the calculated spectra is defined by light ($Z < 7$) and heavy ($Z > 6$) nuclei, which contribute to low ($y < 40 \text{ keV}/\mu\text{m}$) and high ($y > 4 \text{ keV}/\mu\text{m}$) linear energy events. Behind a range shifter of 135 mm-we the spectrum is peaked at 100 keV/μm, while the peak is shifted to 300 keV/μm when the thickness of the range shifter is increased to 159.6 mm-we.

Microdosimetry spectra for 152 MeV/u $^4\text{He}$, 176 MeV/u $^7\text{Li}$ and 290 MeV/u $^{12}\text{C}$ ions corresponding to the same range in water were calculated with MCHIT at various depths inside a water phantom. The resulting spectra were used as an input to MK model in order to estimate the RBE$_{10}$ corresponding to 10% survival of Human Salivary Gland (HSG) cells after irradiation. The obtained RBE$_{10}$ as a function of depth is shown in figure 2. Microdosimetry spectra were also calculated at same positions for simulations when nuclear fragmentation reactions are neglected. The corresponding RBE$_{10}$ is also presented in figure 2 for comparison. One can see that nuclear fragmentation causes a reduction of RBE$_{10}$ in case the radiation field would be composed only by primary ions. The RBE$_{10}$ for helium and lithium is only significantly decreased at the far end of the ion range while for carbon ions the RBE$_{10}$ values at all investigated positions are decreased by less than 10%. This shows that the loss of a primary carbon ion and yield of secondary fragments shall result in less biological effect for this particular end-point.

4. Conclusions

Microdosimetry spectra for hydrogen, helium, lithium, carbon and silicon ions in the energy range relevant to GCR can be successfully calculated with Geant4/MCHIT. The measurements of microdosimetry spectra behind shielding open another possibility to validate Monte Carlo transport codes. Nuclear fragmentation reactions that happen in the shielding of a spacecraft decrease the RBE$_{10}$ for survival of HSG cells with respect to primary nuclei. Therefore, not only the physical dose, but also biological effects of radiation can be reduced by such shielding.
Figure 1. Microdosimetry spectra for (a) \(^1\)H, (b) \(^4\)He, (c-d) \(^7\)Li, (e-f) \(^{12}\)C and (g-h) \(^{28}\)Si at different water-equivalent depths. Experimental data from [15, 16] are shown.
Figure 2. RBE\textsubscript{10} for HSG cells as a function of depth in water after irradiation by light nuclei. Solid line present expected results calculated by MCHIT+MK models when all interaction processes are taken into account in simulations. Dashed lines present hypothetical RBE\textsubscript{10} in the absence of nuclear fragmentation of the considered beams.

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