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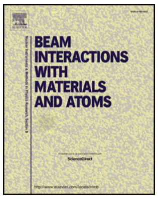

Validation of Gean4 physics models for nuclear beams in extended media

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ABSTRACT

The physical and biological processes induced by energetic heavy ions in extended media are of great importance for human space exploration and ion therapy. In this paper we check the validity of some nucleus-nucleus inelastic collision models in Geant4 for the transportation of heavy nuclei in materials. The depth-dose distributions of ^{12}C and ^{56}Fe beams in extended media and the yields of secondary fragments have been simulated by G4WilsonAbrasion model, G4BinaryLightIon model and G4QMD model. Then the propagation of heavy nuclei through materials used in space industry and the angular distributions of secondary neutrons are also simulated for further validation of the models. By comparing the simulated results with experimental data, it is found that the G4QMD model gives the best results. The implication for estimating the radiation environment on Mars caused by GCRs is also discussed.

1. Introduction

The transportation of energetic particles in media is an important subject in many fields [1,2]. In medical physics, heavy ion therapy as a cancer treatment method has been much discussed in recent years [3–6]. Comparing with X-ray and γ-ray, it has many advantages. The depth-dose distribution curves of heavy ions have a Bragg peak at the end of range [7], and the relative biological effectiveness of heavy ions are higher than X-ray and γ-ray. It can kill cancer cells more effectively and causes less damage to normal tissues. Due to these advantages, heavy ion therapy is expected to be an effective method to cure malignant tumours. A typical example is carbon ion therapy which is rapidly developing [8,9] due to the excellent characteristics in dose delivery and a reduced scattering [10].

In space exploration, protection from space radiation is one of the major concerns. In 2012, NASA launched the Mars Science Laboratory Curiosity rover [11]. The major objective of the rover is to measure the radiation environment of Mars at present and estimate the habitability of Mars in the past. At present, the Martian atmosphere is much thinner than earth atmosphere and there is no global magnetic field on the Mars [12]. A large number of charged particles continuously reach the Martian surface causing a high radiation environment which can cause irreparable DNA damage in cells [12]. Correctly estimating the radiation environment on Mars is important for future manned Mars exploration.

Although the intensities of heavy ions like ^{12}C, ^{56}Fe in the GCRs are very low comparing with proton, the relative biological effectiveness of heavy ions is greater than proton [13]. The interaction of nuclei with materials can be simulated by some particle transport codes, such as PHITS [14–16], MCNP [17,18], FLUKA [19–21] and Geant4 [22–25]. Among which, Geant4 is a free particle transport toolkit based on Monte Carlo method [26]. The users can choose the particles and the physics models according to the specific type of application. Geant4 has been developed rapidly in the last few years, and has been widely used in medical physics, high energy physics and radiation protection [27]. In recent years, more and more studies on the transportation of heavy nuclei are based on Geant4 [13,28–31]. In Ref. [13], Pshenichnov et al. did some pioneering work. In this work, the passage of heavy nuclei in extended media was simulated by G4WilsonAbrasion model and G4BinaryLightIonReaction model. Due to the imperfection of the physics models and the obsolescence of the code, the results are not satisfactory, especially for the yields of secondary fragments. It is necessary to do further researches along this direction.

The Geant4 toolkit is kept developing all the time and the models in Geant4 are still being updated. After the version 9.1 [10], a new nucleus-nucleus inelastic collision model named G4QMD has been added into Geant4. It's meaningful to test the validity of these models. This work aims to simulate ^{12}C and ^{56}Fe ion beams projected into water, polyethylene, aluminum and copper by using G4BinaryLightIon model,

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G4QMD model, G4WilsonAbrasion model and investigate the validity and accuracy of these models by comparing simulation results with experimental data. We hope to find a model that can well describe the physical process of heavy nuclei in media and can be used to simulate the radiation environment on planets caused by GCRs.

2. Brief description of code

All of the simulations in this work are based on Geant4 (version 10.1). Geant4 has several different models which are used to describe nucleus-nucleus collision, such as: G4QMD, G4EMDissociationModel, G4WilsonAbrasion/G4WilsonAblation, G4BinaryLightIonReaction, G4Incl/G4Abla. In present work, we focus on the validity of G4BinaryLightIonReaction, G4WilsonAbrasion and G4QMD for heavy nuclei.

The G4BinaryLightIonReaction model is an extension of G4BinaryCascade model [32]. It can be used to describe light ion reactions. The lighter of the collision nuclei is considered as the projectile [33]. In this model, nucleons are interacted one-by-one with target nucleus, using the original Binary cascade model. This model has some limitations such as neglecting participant-participant scattering, using simple time independent nuclear potential. It is applicable for light ion reactions with energies up to 10 GeV/n [13].

The G4WilsonAbrasion model is another approach to simulate nucleus-nucleus interactions. It is a simplified macroscopic model which based largely on geometric arguments [34]. In this model, when the projectile nucleus collides with target nucleus, the nucleons in the overlap region are abraded and form a “fireball”. Respectively, other nucleons in the projectile and target nuclei are treated as spectators and their momentum are little changed [35]. Then the excited nuclear prefragments are de-excited via emission nucleons and light clusters. The simulations with G4WilsonAbrasion model are faster than with G4BinaryLightIonReaction model, but the results are less accurate [13].

The G4QMD model is an alternative approach in Geant4 to simulate nucleus-nucleus inelastic interactions. All nucleons are considered as participant particles and participant-participant scatterings are included. Each nucleon is treated as a gaussian wave packet [36]. After the time evolution of the QMD system, fragment nuclei from the reaction are identified [36]. Fragments are passed on to the de-excitation models of Geant4 after the calculation of their excitation energy. The detailed description of these models can be found in Geant4 Physics Reference Manual.

3. Results and discussion

In this paper, we will simulate the transportation and interaction of ^{12}C and ^{56}Fe in extended media including water and polyethylene at first. In simulation, the dose distribution and the production of secondary fragments are calculated. After comprehensive analysis, we will select some optimal models. Then the optimal models will be used to simulate the propagation of heavy ions through materials used in space shielding, such as Al and Cu.

3.1. Secondary fragments and Bragg peak of ^{12}C beams in water

The dose distributions and secondary fragments of 200 A MeV and 400 A MeV ^{12}C beams in water are obtained by using G4WilsonAbrasion model (G4 abrasion), G4BinaryLightIon model (G4 BIC) and G4QMD model. A cubical water phantom of 150 (x) × 150 (y) × 400 (z) mm^3 is divided into 1600 slabs along z axis uniformly. To get the average linear energy transfer, the energy deposition in each slab is recorded. The number of secondary particles within a 10° cone around the beam axis in each slab is also recorded during the simulation [37], which is then divided by the number of incident particle to get the normalized yields. The results are shown in Figs. 1–3, and the experimental data derived from Ref. [37] are also included. The relative deviations between simulation results and experimental data are also calculated and shown in Table1.

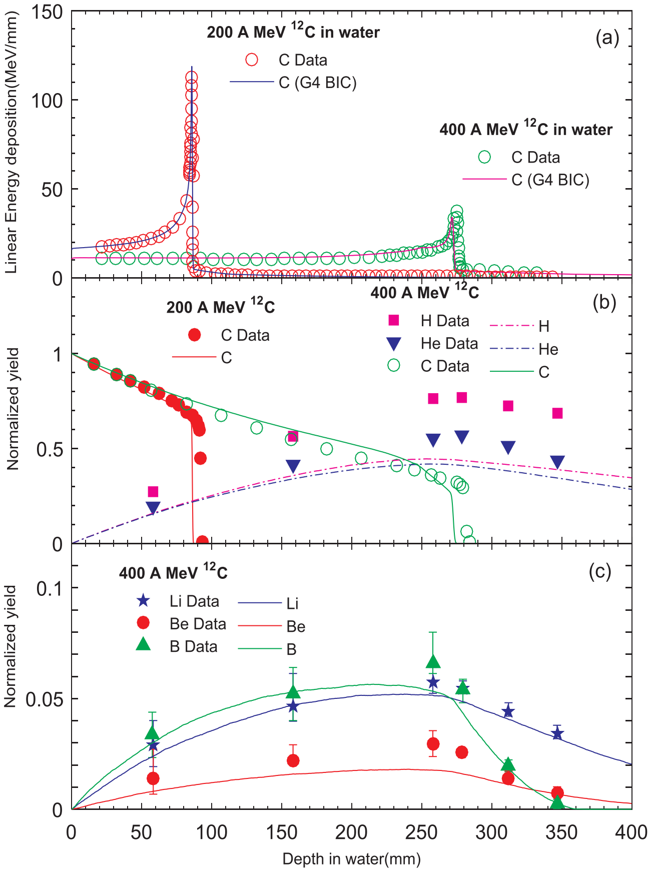

Fig. 1. Depth-dose profiles and secondary fragments of ^{12}C beams in water simulated by G4BinaryLightIon (G4 BIC) model:(a) linear energy deposition of carbon; (b) the normalized yields of hydrogen, helium and carbon; (c) the normalized yields of lithium, beryllium and boron. The experimental data (shown by various symbols) are taken from Ref. [37]. The simulated results are shown by various lines.

It can be seen from Fig. 1(a) that the curve of energy deposition increases slowly with the increasing of depth at first, at a given depth the curve increases dramatically until the maximum value is reached, and then drops sharply forming the Bragg peak. Comparing with X-ray and γ-ray, the structure of the Bragg peak is one of the advantages of heavy ion therapy. Comparing the energy deposition curve of 200 A MeV ^{12}C with 400 A MeV ^{12}C, one can also see that for higher primary beam energy, the position of the Bragg peak is deeper but the height of the peak is lower. For 200 A MeV ^{12}C, about 70% of primary carbon can reach the Bragg peak position and the rest undergo fragmentation on the way. While for 400 A MeV ^{12}C, about 70% of primary nuclei undergo fragmentation before the Bragg peak is reached.

From Fig. 1(b) and (c), one can see that the energetic carbon ions produce lots of secondary fragments in water and the production of all secondary fragments increases with depth before the position of Bragg peak. For the particles that have large charge and inelastic cross section, their productions fall off rapidly after the Bragg peak (Fig. 1(c)). While for H and He, their productions decrease slowly (Fig. 1(b)).

By comparing simulation results with experimental data, it can be found that the depth-dose distributions simulated by three models are consistent with the experimental data. Each model can correctly reproduce the Bragg peak with its position and height. However, the productions of secondary fragments simulated by different models differ a lot from each other, which can also be seen from the values of deviations between simulation results and experimental data as shown

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