PROCEEDINGS OF SCIENCE

Model for the calculation of the production rates of cosmogenic nuclides in meteorites based on Geant4 simulation software

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The cosmic-ray particles represent the valuable source of information about different celestial objects. Bombarding the bodies of the Solar System not protected with the atmosphere, they cause the generation of cosmogenic nuclides. Studying the production rates of cosmogenic nuclides in bodies, it is possible to derive important information about these bodies such as shielding capabilities, exposition time in the Solar System, dimensions or in case of meteorites also the time from the fall on the Earth. In our contribution, we would like to present our model for the simulation of the interaction of the primary galactic cosmic-ray protons with bodies. The model is based on Monte Carlo simulation software Geant4. The spherical body with predefined dimension, chemical composition and density is simulated which is bombarded by galactic protons with energies distributed according to the used energy spectrum. Within the spherical body the concentric shells with decreasing radius are considered which define the region where the fluxes of secondary protons and neutrons are calculated. In order to calculate the production rates of nuclides, the separate set of cross sections were used. The model calculates the production rates for selected cosmogenic nuclides.

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1. Introduction

Meteoritic and asteroidal material represent the source of valuable information about the history and the formation of the Solar System. These bodies are exposed to the bombardement of cosmic-ray particles. As they are not protected by the atmosphere, the particles directly interact with the material of the parent body which leads to the generation of secondary particles mainly protons and neutrons. These particles possess further enough energy to create further reactions within the material and result into the creation of cosmogenic nuclides. Studies of the production rates of cosmogenic nuclides offer information about the exposition time of bodies in the Solar system, time from the fall of the sample on the ground, shielding capabilities of the material or the original dimensions of the primary body. In order to be capable to derive all the information, it is necessary to confront the laboratory measurements with the predictions resulting from the simulation-based model. There are several already published works [1], [2], [3], [4], [5], [6] which focus on the simulations of the bombardement of extraterrestrial material by cosmic-ray particles. In the presented work, we present our own developed model for the calculation of the fluxes of secondary particles and further for the production rates of the cosmogenic nuclides.

2. Model

The presented model is based on the Monte Carlo simulation software Geant4 [7], [8]. The model simulates a sphere with predefined chemical composition, homogeneous density and dimension. There are concentric spheres created within the body with decreasing diameter according to a predefined incress. In these regions the fluxes of secondary particles and production rates are studied. These fluxes are further used with the set of cross sections to calculate the production rates of desired cosmogenic nuclides.

The sphere is isotropically bombarded by primary galactic cosmic-ray protons with energies distributed according to the energy spectrum from [9]

$$J(E, \theta) = C\frac{E(E+2E_0)(E+K)^{-\gamma}}{(E+\theta)(E+2E_0+\theta)} \quad (1)$$

In Equation 1, E is proton kinetic energy in MeV, E_0 is the rest energy, θ is the solar modulation parameter in MeV (we adopted 550 MeV), C = 1.244×10^{6} $cm^{-2}s^{-1}MeV^{-1}$, K = $780e^{(-2.5x10-4E)}$ and γ = 2.65 is the spectral index. The protons with energies up to 20 GeV have been simulated. In Figure 1, we present the schematic view of our model.

The model has been tested in case of well studied meteoritic sample Knyahinya. This sample was previously studied in [3] and [10]. The results of these works serve as a cross-check of our calculations. We have simulated the meteorite with radius 45 cm, density 3.35 g/cm^3 and incress 2.5 cm between the different concentric spheres. The abundance of different elements was considered as following - O 42%, Na 0.7%, Mg 15.05%, Al 1.19%, Si 21.5%, P 0.1%, S 0.5%, K 0.092%, Ca 1.47%, Ti 0.07%, Cr 0.4%, Mn 0.28%, Fe 16.47%, Co 0.01%, Ni 0.14%. These parameters copy the input parameters used in [3]. 15.1 millions of primary protons were simulated.

The fluxes of secondary protons and neutrons were used to calculate the production rates of cosmogenic nuclides as [2]

$$Pj(d) = \sum_i \frac{c_i N_A}{A_i} \sum_k \int_0^{\infty} \sigma_{ijk}(E_k) J_k(E_k)\, dE_k \quad (2)$$

where N_A is Avogadro constant, A_i the mass of target element i, c_i the concentration of the target element i in g/g and k is the index for the reaction particle type (primary proton, secondary proton and secondary neutron). $\sigma_{i,j,k}(E)$ represents the excitation function (or cross section) for the production of nuclide j from target element i by the reactions induced by particles of type k. J_k is the differential flux density of particles of type k.

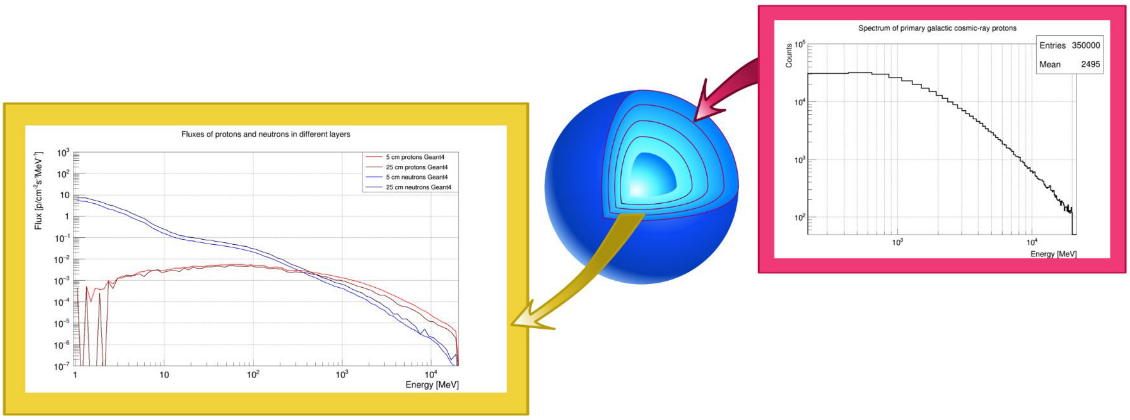

Figure 1. Schematic view of the developed model. Right plot represents the energy spectrum of 350 000 primary protons which bombard the sphere. Left plot represents the fluxes of protons and neutrons for different layers within the sphere. Credit: Justína Nováková, Faculty of Natural Sciences, Comenius University in Bratislava.

3. Results

We present the results of calculated fluxes in different depths for protons and neutrons, see Figures 2 and 3. The results are compared with the calculated fluxes from [10].

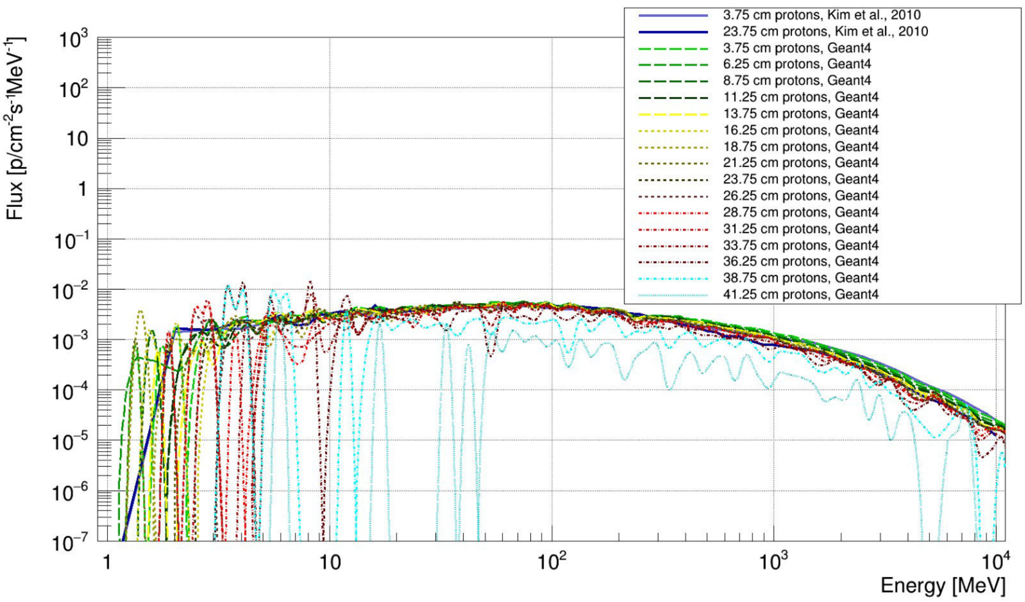

Figure 2. Fluxes of protons in different depths of Knyahinya meteorite. Fluxes near the surface and halfway to the center of the sample from [10] are introduced.

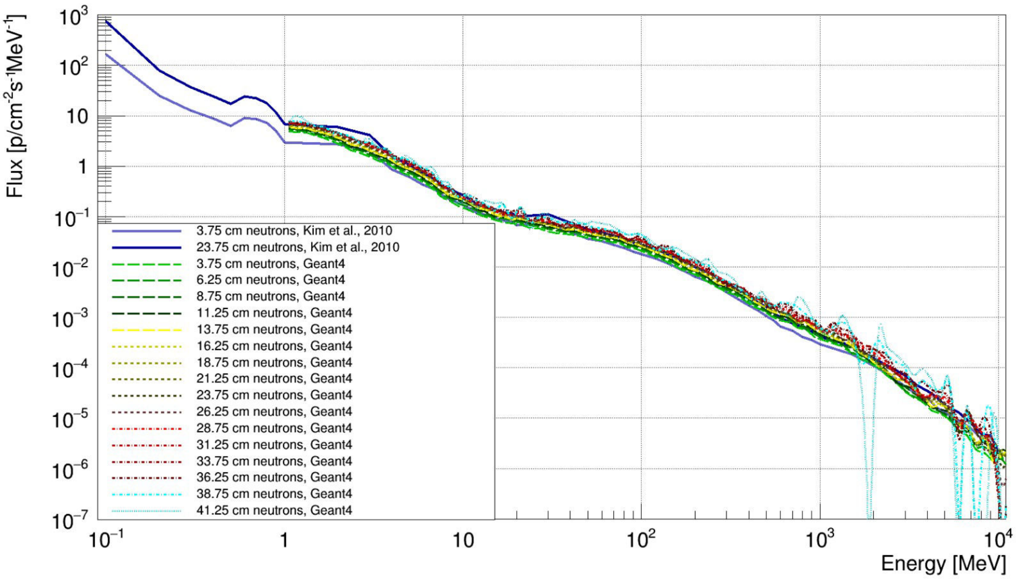

Figure 3. Fluxes of neutrons in different depths of Knyahinya meteorite. Fluxes near the surface and halfway to the center of the sample from [10] are introduced.

4. Discussion and Conclusion

We present the developed model which calculates the production rates of the isotopes of cosmogenic nuclides based on the Monte Carlo simulation software Geant4. We have tested the applicability of our model in case of meteoritic sample Knyahinya which was previously well studied. We compare the resulting fluxes of protons and neutrons separately for different depths with the calculated fluxes from [10] where the authors used MCNPX simulation software. We can assume that our predictions are in good agreement with these calculations. It is possible to see that for protons the relative values of flux is decreasing with increasing depths. On the other side, the relative values of fluxes for neutrons is increasing with increasing depth. We can assume that our model is applicable for further calculations of cosmogenic nuclides.

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