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A self-consistent model for the production of cosmogenic nuclides on the Moon with Geant4

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Abstract

A numerical model is built to simulate the production of cosmogenic nuclides based on Geant4 (GEometry ANd Tracking). Some modifications have been made for cross sections in Geant4 using the experimental data or the other proper model and the contributions of all secondary particles caused by cosmic rays are included in our simulation model. Our simulation results suggest a substantial contribution of the secondary charged pions to the production rates of ^{10}Be and ^{14}C, as high as 21.04% for ^{10}Be and 21.36% for ^{14}C, respectively. Within one set of self-consistent parameters, the simulation results of the production rates of the cosmogenic nuclides, ^{53}Mn, ^{36}Cl, ^{41}Ca, ^{26}Al, ^{10}Be, and ^{14}C, agree well with the measured data from Apollo 15 drill core. This model provides users a validated approach to study the production of cosmogenic nuclides on the planet surface and in the meteorites.

1. Introduction

The Moon is permanently bombarded by cosmic-ray particles which consist of galactic cosmic rays (GCR) and solar cosmic rays (SCR). Since the Moon is an airless body and has no global magnetic field, the lunar surface is directly exposed to the external particles. For the incident particles with energies on the order of 1 GeV or higher, a cascade of many secondary particles (neutrons, protons, pions, and others) are produced. Cosmogenic nuclides, such as ^{3}He, ^{10}Be, ^{14}C, ^{21}Ne, ^{22}Ne, ^{22}Na, ^{26}Al, ^{36}Cl, ^{36}Ar, ^{38}Ar, ^{40}K, ^{41}Ca, ^{53}Mn, ^{60}Co, are produced by primary cosmic-ray particles and their secondary particles in the irradiated materials.

The radioactive cosmogenic isotopes are widely used to date the exposure ages of rocks and soils. The production rates of the radioactive cosmogenic nuclides can also be used to reconstruct the average solar modulation potential in the last million years and explore the evolution history of solar activity and cosmic-ray itself. A clear understanding of the production process of cosmogenic nuclides is the basis for above applications.

Much work has been done to study the production process of cosmogenic nuclides [1-4]. Those work considered the contributions of protons and neutrons, the prominent composition of the secondary particles which are produced by primary cosmic-ray particles in the materials. The contributions of other secondary particles, such as pions, were ignored because of their small contributions [2].

In this work, we will consider the production and transportation of the pions and include their contribution to the production of cosmogenic nuclides. A numerical simulation model is built based on Geant4. Some modifications have been made for cross sections in Geant4 using the experimental data or the other proper model and the contributions of all secondary particles caused by cosmic rays are included in our simulation.

2. Computational Model Based on Geant4

Geant4 (GEometry ANd Tracking) is a well-developed Monte Carlo toolkit which is used for the simulation of the passage of particles through matter [5]. It provides a comprehensive set of physical processes handling the diverse interactions of particles with matter across a wide energy range, starting from about 100 eV to the TeV.

The energy spectra of GCR flux and SCR flux are two of the most important input sources in Geant4 simulation. In this calculation, we use the analytic form of the GCR differential energy spectra given by Usoskin [6]. The SCR differential flux per unit of rigidity is given by Reedy et al. [3]. The production rates of ^{10}Be, ^{14}C, ^{26}Al, ^{36}Cl, ^{41}Ca, and ^{53}Mn are calculated with the same set of parameters for GCR and SCR. The modulation parameter is chosen as 550 MV and the integral fluxes of the proton and alpha particles are 3.498 and 0.339 per cm^2 per second, respectively. The integral flux of SCR (Ep > 10 MeV) is 134 cm^{-2} s^{-1} and R_0 is 80 MV.

The Moon is modeled as a spherical body with a radius of 1738 km as the target. The material and density in the lunar body is based on the data of Apollo 15 drill core (15001) [7].

3. Results

The contributions of different processes, calculated by Geant4, to the production of the cosmogenic nuclides caused by GCR are listed in Table 1. The sum of the contribution of π^+ and π^- to the production of ^{10}Be and ^{14}C is 21.04%, 21.36%, respectively. The contribution of π^+ and π^- to the production of ^{26}Al, ^{53}Mn and ^{36}Cl is lower, just 5.77%, 4.01% and 3.4%, respectively. The neutron capture reaction, ^{40}Ca (n, γ) ^{41}Ca, is the dominative process for ^{41}Ca production. It is worth noting that the contribution of charged pions to cosmogenic nuclei production is negligible when the input particle source is SCR protons.

Table 1: The contributions of different processes to the production of the cosmogenic nuclides ((n,x), (p,x), and (α, x) represent neutrons, protons, and α particles induced reactions, respectively).

	(n, x)	(p, x)	(π^-, x)	(π^+, x)	Decay	(α, x)	Neutron Capture	else[a]
^{10}Be	56.08	19.94	15.87	5.17	0	1.71	0	1.23
^{14}C	63.36	13.67	13.88	7.48	0.39	0.53	0	0.69
^{26}Al	72.49	14.08	2.72	3.05	6.63	0.46	0	0.57
^{53}Mn	70.36	15.52	1.69	2.32	9.70	0.14	0	0.27
^{36}Cl	83.76	12.18	2.33	1.07	0	0.35	0	0.31
^{41}Ca	0.64	0.51	0.22	0.32	0.03	0.02	98.17	0.09

One can see from Figure 2 that the production rates calculated by this model are in good agreement with the measurements [8-9].

4. Conclusions

Above results may give a new insight into the production of the cosmogenic nuclides and show that our model provides a self-consistent approach to simulate the cosmogenic nuclides production and for the study of the historic evolution of solar activities and cosmic rays.

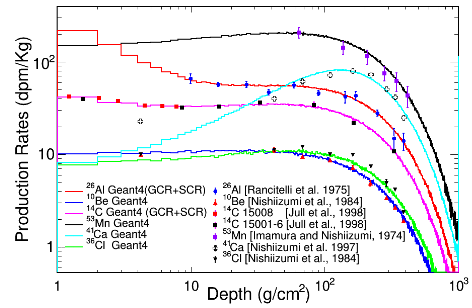

Figure 2: The simulation results and the experimental data of the production rates of ^{10}Be, ^{14}C, ^{26}Al, ^{36}Cl, ^{41}Ca, and ^{53}Mn.

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