A New Insight into the Production of Cosmogenic Nuclides on the Moon with Geant4 Simulation. Xiaoping Zhang*, Yong Li and Aoao Xu, Lunar and Planetary Science Laboratory, Macau University of Science and Technology, Macau, China (* xpzhangnju@gmail.com)

**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. The GCR particles have a wide energy range from a few MeV to much larger than 100 GeV per nucleon at 1 AU. For the 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, \(^{23}\)Na, \(^{26}\)Al, \(^{36}\)Cl, \(^{38}\)Ar, \(^{40}\)K, \(^{41}\)Ca, \(^{53}\)Mn, \(^{40}\)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].

Lal [5] pointed out that the production and transportation of pions are important in interpreting the data of cosmogenic nuclides. But no further work along this direction has been found yet. In the calculation of Kim et al. [1], different parameters of GCRs, which determine the energy spectrum and intensity of the GCR flux, are applied for different nuclides to fit the experimental data. One possible reason is the ignorance of the contribution of the pions to the production of the cosmogenic nuclides.

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.

**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 [6]. 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. The GCRs, originated from the outside solar system, are modulated in the inner solar system by the interactions with the magnetic fields created by solar plasma, which varies with solar activity [7]. In this calculation, we use the analytic form of the GCR differential energy spectra given by Usoskin [8]. The SCR differential flux per unit of rigidity is given by Reedy, Arnold, and Nishiizumi [3, 9]. 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 (E\(_p\) > 10 MeV) is 134 cm\(^{-2}\) s\(^{-1}\) and \(R_p\) 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) [10, 11]. The composition (mass percent) of the material is set as follows: SiO\(_2\) (46.4%), TiO\(_2\) (1.83%), Al\(_2\)O\(_3\) (10.8%), FeO (18.7%), MnO (0.23%), MgO (11.5%), CaO (8.5%), Na\(_2\)O (0.4%), K\(_2\)O (0.3%). We assume that this composition represents the average composition of the lunar soil with a uniform density of 1.93 g/cm\(^3\).

The following physical processes and models are included in the physical list in our simulation: (1) Electromagnetic: G4EmStandardPhysics. (2) Hadron Inelastic Physics: G4HadronPhysicsQGSP-BIC-HP. In the simulation, we calculate the production rates of cosmogenic nuclides directly.

**Results:** The particle fluxes of protons, neutrons and pions which are produced by GCR particles in the lunar sample are calculated and the spectra of the particle fluxes at the depth of 50 g/cm\(^2\) are shown in Figure 1. One can see that the intensity of \(\pi^+\) flux and \(\pi^-\) flux is much lower than that of the neutron’s but not much
The contributions of different processes, calculated by Geant4, to the production of the cosmogenic nuclides caused by GCR are listed in Table 1 [12]. The sum of the contribution of $\pi^+$ and $\pi^0$ to the production of $^{10}$Be and $^{14}$C is 21.04%, 21.36%, respectively. The contribution of $\pi^+$ and $\pi^0$ 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 [13], $^{40}$Ca (n, $\gamma$) $^{41}$Ca, is the dommative 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.

![Image](http://example.com/image.png)

Figure 1. The fluxes of neutrons, protons, $\pi^+$ and $\pi^0$ in the lunar sample calculated by Geant4.

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

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>(n, x)</th>
<th>(p, x)</th>
<th>($\pi^+$, x)</th>
<th>($\pi^0$, x)</th>
<th>Decay</th>
<th>(α, x)</th>
<th>Neutron Capture</th>
<th>c/bc</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{10}$Be</td>
<td>56.08</td>
<td>19.94</td>
<td>15.87</td>
<td>5.17</td>
<td>0</td>
<td>1.71</td>
<td>0</td>
<td>1.23</td>
</tr>
<tr>
<td>$^{14}$C</td>
<td>63.36</td>
<td>13.67</td>
<td>13.88</td>
<td>7.48</td>
<td>0.39</td>
<td>0.53</td>
<td>0</td>
<td>0.69</td>
</tr>
<tr>
<td>$^{26}$Al</td>
<td>72.49</td>
<td>14.08</td>
<td>2.72</td>
<td>3.05</td>
<td>6.63</td>
<td>0.46</td>
<td>0</td>
<td>0.57</td>
</tr>
<tr>
<td>$^{53}$Mn</td>
<td>70.36</td>
<td>15.52</td>
<td>1.69</td>
<td>2.32</td>
<td>9.70</td>
<td>0.14</td>
<td>0</td>
<td>0.27</td>
</tr>
<tr>
<td>$^{36}$Cl</td>
<td>83.76</td>
<td>12.18</td>
<td>2.33</td>
<td>1.07</td>
<td>0.35</td>
<td>0</td>
<td>0.31</td>
<td></td>
</tr>
<tr>
<td>$^{41}$Ca</td>
<td>0.64</td>
<td>0.51</td>
<td>0.22</td>
<td>0.32</td>
<td>0.03</td>
<td>0</td>
<td>98.17</td>
<td>0.09</td>
</tr>
</tbody>
</table>

One can see from Figure 2 that the production rates calculated by this model are in good agreement with the measurements [14-18].

Conclusions: A numerical simulation model is built based on Geant4 to simulate the production of cosmogenic nuclides. Some modifications have been made for cross sections in Geant4 using the experimental data or other proper model and the contributions of all secondary particles caused by cosmic rays are included in our 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, $^{10}$Be, $^{14}$C, $^{26}$Al, $^{36}$Cl, $^{41}$Ca, and $^{53}$Mn, agree well with the measured data from Apollo 15 drill core and suggest that the average solar modulation potential over the last million years is about 550 MV. Above results may give a new insight into the production of the cosmogenic nuclides and show that our model provide a validated approach to simulate the cosmogenic nuclides production and for the study of the historic evolution of solar activities and cosmic rays.

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