Cosmogenic Nuclei Production Rate on the Lunar Surface

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Abstract

A physical model of Geant4-based simulation of galactic cosmic ray (GCR) particles interaction with the lunar surface matter has been developed to investigate the production rate of cosmogenic nuclei. In this model the GCRs, mainly very high energy protons and α particles, bombard the surface of the Moon and produce many secondary particles such as protons and neutrons. The energies of proton and neutron at different depths are recorded and saved into ROOT files, and the analytical expressions for the differential proton and neutron fluxes are obtained through the best-fit procedure under the ROOT software. To test the validity of this model, we calculate the production rates of long-lived nuclei $^{10}$Be and $^{26}$Al in the Apollo 15 long drill core by combining the above differential fluxes and the newly evaluated spallation reaction cross sections. Numerical results show that the theoretical production rates agree quite well with the measured data. It means that this model works well. Therefore, it can be expected that this model can be used to investigate the cosmogenic nuclei in lunar samples returned by Chinese lunar exploration program and can be extended to study other objects, such as the meteorites and the Earth’s atmosphere.

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I. INTRODUCTION

Galactic Cosmic Rays (GCRs) are high energy particles that pass through the interstellar space in our Milky Way galaxy. The most abundant components of GCRs are protons and α particles. These energetic particles can interact with the matters both in the interstellar space and interplanetary space. The former can be used to investigate the origin and evolution of GCR itself \[1\], and the latter provide us an useful tool to investigate the cosmic ray exposure history of extraterrestrial bodies such as the planets and the meteorites \[2–6\]. Among these bodies the Moon is an unique one in our solar system. Due to the atmosphere free and old surface, the Moon has recorded rich information about the solar system evolution and variations of the galactic cosmic rays (GCRs) in the past several billion years. GCRs can bombard directly the solid surface of the Moon. The interactions of GCRs (primary particles) and the matters of the lunar surface can produce many protons, neutrons and mesons (secondary particles) and some nuclei that can not be synthesized by thermonuclear reactions. These nuclei are called cosmogenic nuclei. The materials returned by Apollo and Luna missions has provided good opportunities to study the cosmogenic nuclei with very high accuracy. It can be expected that the lunar samples returned by Chinese lunar exploration program in the near future will promote enormously the development of lunar and planetary science including the investigation of cosmogenic nuclei. To provide reliable method to interpret the measured data in the near future, it is time to investigate this subject beforehand from theoretical points of view.

In principle, if both the concentration and production rate of a stable cosmogenic nuclei are known, one can calculate the cosmic-ray exposure (CRE) age of that material. The concentration of nuclei can be measured accurately in laboratory by accelerator mass spectrometer (AMS), but the calculation of the absolute production rate is much more difficult in general speaking. Fortunately, there is an important exception. If the CRE age is much longer than the half-life of a given radioactive cosmogenic nucleus, its production rate equals to the activity that can be measured directly (see below). Therefore, most of the CRE ages are determined by using the radioactive-stable nuclei pairs, for instance \(^{10}\)Be-\(^{21}\)Ne, \(^{26}\)Al-\(^{21}\)Ne, \(^{36}\)Cl-\(^{36}\)Ar \[6\]. The CRE ages of lunar rocks on the rim of lunar craters are particularly important to date the impact events that excavated these rocks to GCR irradiation \[6\]. These ages can be used to calibrate the relative ages of lunar surface determined by the morphology
craters.

In this work, we develop a Monte Carlo model based on Geant4 software package to calculate the production rate of cosmogenic nuclei. Before applying this model to extensive studies, it is needed to test the validity of it. To this end, we choose the Apollo 15 long drill core as research object. It is because its chemical composition, location, shielding depth of samples are known clearly. In addition, Apollo 15 drill core is the least disturbed sample among the three deep drill cores, Apollo 15, 16 and 17. The production rates of long-lived nuclei $^{10}$Be and $^{26}$Al are calculated and compared with experimental data. This paper is organized as follows: in section 2 we describe the theoretical model, and in section 3 we discuss the numerical results, a summary and outlook is given in section 4.

II. THE THEORETICAL MODEL

The shape and size of meteoroids (i.e., the precursor of the meteorites) are difficult to determine directly from that of meteorites due to the unknown degree of ablation and fragmentation. For simplicity, the meteoroids are usually regarded as a sphere with radius $R$ and uniform chemical composition. Under this assumption, the general formula of the production rate of cosmogenic nuclei $i$ at the depth $d$ under the surface of a meteoroid is shown as follows [8, 9]:

$$P_i = \sum_k \sum_j N_j \int J_k(E, R, d)\sigma_{j,k}(E)dE,$$

where $N_j$ is the concentration of element $j$ in the meteoroid, $J_k(E, R, d)$ is the differential flux of particle $k$ (in this work we only consider protons and neutrons), $\sigma_{j,k}(E)$ is the excitation function of the involved nuclear reaction for the production of nuclide $i$ from element $j$ induced by particle $k$ at incident energy $E$.

Before the meteoroids impacting the Earth’s atmosphere, they are irradiated by galactic cosmic rays. In this work, we take the most abundant proton and $\alpha$ particles in GCRs as primary particles, which bombard the surface of meteoroids isotropically. The fluxes of proton and $\alpha$ particle are taken as follows [10]:

$$J_p(E, M) = C_p \frac{E(E + 2m_p c^2)}{(E + M)(E + M + 2m_p c^2)}(E + M + x_p)^{-\gamma_p},$$

$$J_\alpha(E, M) = C_\alpha \frac{E(E + 2m_\alpha c^2)}{(E + M)(E + M + 2m_\alpha c^2)}(E + M + x_\alpha)^{-\gamma_\alpha}.$$
In these two formulas $E$ denotes the energy per nucleon in MeV, $M$ is the solar modulation parameter in MV, and $m_p c^2 = 938$ MeV is the rest mass of proton. In Eq.(2) $C_p = 1.244 \times 10^6 (\text{cm}^2 \text{s MeV})^{-1}$, $x_p = 780 \exp(-2.5 \times 10^{-4}(E + M))$, $\gamma_p = 2.65$. In Eq.(3) $C_\alpha = 2.23 \times 10^5 (\text{cm}^2 \text{s MeV})^{-1}$, $x_\alpha = 660 \exp(-1.4 \times 10^{-4}(E + M))$, $\gamma_\alpha = 2.77$. These formulas are implemented into the Geant4 code to sample the primary protons and $\alpha$ particles.

When the high energy protons and $\alpha$ particles bombard the meteoroid, they will interact with the atoms and nuclei therein. The dominant processes are ionizing energy loss and spallation reactions. By ionizing energy loss the energy of primary particles will decrease continuously. And by the spallation reactions many secondary particles, such as protons, neutrons and mesons, are produced. The secondary particles, especially neutrons will induce lower-energy ($E < 100$ MeV) reactions, and the very low-energy neutrons will account for neutron capture reactions.

As shown in Eq.(1), in order to calculate the production rate one must search for a method to obtain the differential fluxes of proton and neutron in the irradiated body. The Monte Carlo simulation is a good choice for these calculations. Among various Monte Carlo based software, the Geant4 [11] has been used more and more widely in nuclear physics and space science [12, 13]. In our recent work [14], the neutron fluxes escaped from the lunar surface has been investigated using the Geant4 software. In the present work we will also use this software to calculate the proton and neutron fluxes beneath the meteoroid surface. In order to obtain the differential fluxes of active particles, the energies of primary and secondary proton and neutron at different depths are recorded and saved as ROOT files. Then we obtain the numerical differential fluxes of different particles by analyzing the ROOT file. However, due to the statistical nature of the Monte Carlo method, there are statistical fluctuations in the fluxes. To calculate the production rate of cosmogenic nuclei by Eq.(1), it is necessary to obtain the analytical expressions of proton and neutron fluxes by the best-fit procedure. Once the analytical expressions for fluxes are obtained, one can calculate the production rate of interesting nuclei by combining these fluxes formulas with the nuclear reaction cross sections. The cross sections of proton induced reactions can be taken from experimental data. However, the cross sections for high energy neutron induced reactions are obtained in indirect ways, for instance the thick target irradiation experiment. It is because the neutron is a neutral particle that can not be accelerated to any energy. In this paper we will use the evaluated proton cross sections by Nishiizumi et al. [15] and neutron
cross sections by Reedy [16].

Up to now, the physical model to calculate the production rate of cosmogenic nuclei has been established. After applying this model to extensive studies, it is needed to test the validation of this model. To this end, we choose the lunar drill core as the research object. It is because its chemical composition, location, shielding depth of samples are known clearly. In addition, Apollo 15 drill core is the least disturbed sample among the three deep drill cores, Apollo 15, 16 and 17 [17, 18]. In this case the radius of Moon can be regarded as infinite, and the surface can be seen as a plane. In simulations we establish a sufficient large box filled with the average chemical composition of Apollo 15 drill core [19], the GCRs incident on the upper surface of it. In this work, the box is taken as 100 m long × 100 width × 20 m thickness. This box is filled with uniform lunar soils. The chemical composition is: O (43.0% wt), Si (22.1% wt), Al (7.67% wt), Ca (7.52 % wt), Mg (5.89 % wt), Fe (11.57 % wt), Ti (1.12 % wt), Na (0.332 % wt), and K (0.21 % wt). Here, % wt denotes the weight percentage. The GCRs, sampled according to Eqs.(2) and (3), incident on the upper surface of this box isotropically. Considering both the statistical accuracy and time cost, 5 million particles are sampled.

Once the production rate is calculated one can derive the cosmic ray exposure (CRE) age by using the relations as follows: for a stable cosmogenic nuclide

\[ S = P_s T, \]  

and for a radioactive cosmogenic nuclide with the decay constant \( \lambda \)

\[ R = P_R \lambda^{-1}(1 - e^{-\lambda T}), \]  

where \( T \) is the CRE age and \( S \) (\( R \)) and \( P_s \) (\( P_R \)) are the concentration and production rate of stable (radioactive) nuclide. The basic unit of the cosmogenic nuclei concentration is the number of atoms per gram sample (atoms/(g sample)). In literatures, the concentrations of radioactive nuclei are often reported as radioactive activity, in unit of disintegrations per minute per kilogram (dpm kg\(^{-1}\)). The relationship between the concentration and the activity is

\[ A = \lambda R = P_R(1 - e^{-\lambda T}). \]

From this equation, one can see that if the CRE age is much longer than the half-life of this nuclide, the radioactive equilibrium will be reached and the activity is approximately equal
to the production rate. For this case the measured quantity can be compared directly with
the calculated ones. In this paper, we will choose the nuclei whose half-lives are much longer
than the time by which the lunar core are returned from the Moon and much shorter than
the CRE age. $^{10}$Be ($t_{1/2} = 1.51 \times 10^6$yr), $^{26}$Al ($t_{1/2} = 7.17 \times 10^5$yr) are good candidates.

III. NUMERICAL RESULTS AND DISCUSSIONS

According to the theoretical model described in Sec. 2, we write the Geant4 code to
simulate the transportation and interaction of GCRs in the lunar surface. In simulations,
the neutrons and protons at different depths are recorded and saved as ROOT files, from
which we obtain the differential fluxes for many energy bins. Then the differential fluxes for
neutron and proton at different energy ranges are fitted, respectively. After careful analysis
we found that the proton and neutron fluxes can be expressed quite well by the following
formulas:

\[
J_p(E, d) = \begin{cases} 
  p_0(E + p_1)^{p_2}E/(E + p_3), & (10 \leq E \leq 500) \\
  p_0(E + p_1)^{p_2}, & (500 \leq E \leq 10^4)
\end{cases} 
\]  

(7)

\[
J_n(E, d) = \begin{cases} 
  p_0e^{-E/p_1}, & (10 \leq E \leq 200) \\
  p_0e^{-E/p_1}/(E + p_2), & (200 \leq E \leq 10^4)
\end{cases} 
\]  

(8)

In these formulas the energy $E$ is in MeV, and the $p$’s are depth and chemical dependent
parameters. These formulas are much simpler than that used by Arnold [8] and Reedy [9].
The parameters are determined by the best-fit procedure using the ROOT software. Con-
sidering the limit of space we will not give the numerical results of these parameters. The
proton and neutron fluxes calculated using Eqs.(7) and (8) at depths $d = 100, 200, 300, 400$
$g/cm^2$ are shown in Fig. 1. Here the depth $d$ is the geometrical depth times the density,
the unit is $g/cm^2$. In this figure the fluxes are not normalized to particles/(cm$^2$ s MeV)
since we are interested to the relative magnitude of proton and neutron fluxes. From this
figure, one can see that at high energy range ($E > 200$ MeV) the proton flux is larger than
that of neutron, but at low energy range ($E < 100$ MeV) the neutron flux is larger than
that of proton. It is because the protons beneath the lunar surface include the primary and
secondary ones, but the neutrons are purely secondary particles. The secondary protons
will suffer ionizing loss and stop quickly. As for the cross sections for proton and neutron
induced reactions, the most newly evaluated data are used. The proton cross sections are taken from [15], and the neutron cross sections are taken from [16]. The numerical data for the cross sections involved are shown in Figs. 2-4.

![Proton and Neutron Fluxes](image1)

**FIG. 1.** The proton and neutron fluxes at depths $d = 100, 200, 300, 400 \text{ g/cm}^2$.

![Excitation Function](image2)

**FIG. 2.** The excitation function for proton induced reactions to produce $^{10}$Be on target elements O, Mg, Al, Si, Fe. These data are taken from [15].

From these figures one can see clearly that the excitation functions for these reactions are not smooth. It is because the spallation reaction is a very complex process, the spallation cross sections are very difficult to calculate. Therefore, these functions are obtained by
interpolating the experimental data. Unfortunately, there are only a few data available, even for neutron induced reactions.

Finally, the production rates of cosmogenic nuclei $^{10}$Be and $^{26}$Al are calculated by integrating the depth-dependent fluxes of active particles with the excitation functions of nuclear reactions involved. By using this method, the production rate of $^{10}$Be and $^{26}$Al in Apollo 15
drill core are calculated. In calculations, the production rates result from proton induced reactions and neutron induced reactions are considered. As for proton induced reactions the target elements we considered are O, Mg, Al, Si, Fe for $^{10}$Be, Al, Si, Ca, Ti, Fe for $^{26}$Al. As for neutron induced reactions the cross sections are very scattered. The target elements we considered are O and Si for $^{10}$Be, Al and Si for $^{26}$Al. In order to compare with experimental
data, we introduce two normalization factors for the production rates for neutron and proton induced reactions:

\[ P_R = C_p P_{R,p} + C_n P_{R,n}, \]  

(9)

where \( P_R \) is the total production rate of radioactive nuclei, \( P_{R,p} \) and \( P_{R,n} \) are the contributions due to proton and neutron induced reactions, respectively, calculated using the theoretical model shown in Sec. 2. The main reasons of introducing these factors are as follows: (1) the excitation functions are obtained by interpolating a small number of cross section data, particularly the neutron cross section data are obtained by indirect method; (2) the secondary proton and neutron yields calculated by Geant4 depend on the theoretical model of spallation reactions; (3) the spectrum of primary cosmic rays are assumed to be the current mean value averaged during the solar activity cycle. That is to say the uncertainties on the primary GCR fluxes, secondary particle fluxes and excitation functions in the theoretical model are normalized by two parameters \( P_{R,p} \) and \( P_{R,n} \). These two parameters can be obtained by the best-fit procedure. The theoretical and experimental results are shown in Figs.5-6. In these figures the dotted line and dashed line represent the contributions from proton and neutron induced reactions, respectively, and the solid lines denote the total production rate. The experimental data (denoted by circles) for \(^{10}\text{Be}\) are taken from [17], and the data for \(^{26}\text{Al}\) are taken from [18]. From these two figures one can see that the theoretical production rate of \(^{10}\text{Be}\) and \(^{26}\text{Al}\) agree well with the measured data. In addition, the production rate from neutron induced reactions are larger than that of proton induced reactions. In other words, the neutron reactions dominate the production of cosmogenic nuclei, hence the high-energy neutron reaction cross sections play crucial roles.

IV. SUMMARY AND OUTLOOK

In summary, a physical model based on the Monte Carlo method is proposed to calculate the production rate of cosmogenic nuclei. A Geant4 code has been developed to simulate the transport and interactions of the primary and secondary particles in the extra-terrestrial body. As a test of this model we calculate the production rate of long-lived nuclei \(^{10}\text{Be}, ^{26}\text{Al}\) in the Apollo 15 drill core. The information of neutrons and protons at different depths are recorded and saved as ROOT file. Then the neutron and proton differential fluxes are
obtained by using ROOT software. By combining the differential fluxes and the newly evaluated spallation cross sections the production rates of $^{10}$Be, $^{26}$Al are calculated and compared with experimental data. The results show that the theoretical production rates agree quite well with the measured data for the Apollo 15 long drill core. It means that our model is suitable to investigate the production rate of cosmogenic nuclei in extra-terrestrial body. It is reasonable to believe that this model can be applied to the investigation of production rate of cosmogenic nuclei in meteorites and Earth’s atmosphere. Furthermore, according to the Chinese lunar exploration program, lunar samples will be returned 10 years later or so. When lunar samples are obtained the cosmic ray exposure history of the landing sites is an important subject of research. For instance, the cosmic ray exposure age of the crater rims can be used to date the impact events and to calibrate the geological age of that region defined by the counting rate of impact craters. To reach this goal, it is needed to improve this model by using better physical model of high energy nuclear reactions and more accurate cross sections of proton and neutron induced reactions. As for the former, we can expect that with the improvement of the nuclear reaction model, for instance Liège intranuclear cascade (INCL) model [20], the proton and neutron spectrum can be calculated more and more accurate. In the next, we will study the influences of different nuclear reaction models on the proton and neutron fluxes. As for the latter, the neutron cross sections measured by using the quasi-monoenergetic neutron beams produced by $^7$Li(p,n)$^7$Be reaction within the European HINDAS (High- and INtermediate-energy Data for Accelerator-driven Systems) project [21] will give us unprecedented opportunity to study the production rate of cosmogenic nuclei.

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