Production rates of cosmogenic nuclei on the lunar surface*

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Abstract: A physical model for Geant4-based simulation of the galactic cosmic ray (GCR) particles' interaction with the lunar surface matter has been developed to investigate the production rates 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 protons and neutrons at different depths are recorded and saved as ROOT files, and the analytical expressions for the differential proton and neutron fluxes are obtained through the best-fit procedure using ROOT software. To test the validity of this model, we calculate the production rates of the 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. Our numerical results show that the theoretical production rates agree quite well with the measured data, which means that this model works well. Therefore, it can be expected that this model can be used to investigate the cosmogenic nuclei in future lunar samples returned by the Chinese lunar exploration program and can be extended to study other objects, such as meteorites and the Earth's atmosphere.

Key words: cosmogenic nuclei, Geant4, spallation reaction

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1 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 matter, both in interstellar space and interplanetary space. The former can be used to investigate the origin and evolution of GCRs themselves [1], and the latter provides a useful tool to investigate the cosmic ray exposure history of extraterrestrial bodies, such as the planets and meteorites [2–6]. Among these bodies, the Moon is unique in our solar system. Due to the old age of the surface and its lack of atmosphere, the Moon holds a rich record of the solar system evolution and variations in GCRs over the past several billion years. GCRs can directly bombard the solid surface of the Moon. The interactions of GCRs (primary particles) with the matter of the lunar surface can produce many protons, neutrons and mesons (secondary particles), as well as some nuclei that cannot be synthesized by thermonuclear reactions. These nuclei are called cosmogenic nuclei. The materials returned by the Apollo and Luna missions have provided good opportunities to study these cosmogenic nuclei with very high accuracy. It can be expected that the lunar samples returned by the Chinese lunar exploration program in the near future will considerably promote the development of lunar and planetary science, including the investigation of cosmogenic nuclei. To provide a reliable method of interpreting the measured data in the near future, it is time to investigate this subject beforehand from a theoretical point of view.

In principle, if both the concentration and production rate of a stable cosmogenic nuclide are known, then one can calculate the cosmic-ray exposure (CRE) age of that material. The concentrations of several cosmogenic

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nuclei can be measured accurately in the laboratory with an accelerator mass spectrometer (AMS), but the calculation of the absolute production rate is generally much more difficult. Fortunately, there is an important exception. If the CRE age is much longer than the half-life of a given radioactive cosmogenic nuclide, its production rate is equal to the activity that can be measured directly (see below). Therefore, most of the CRE ages are determined using radioactive-stable nuclide pairs, for instance ^{10}Be-^{21}Ne, ^{26}Al-^{21}Ne, and ^{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 exposed these rocks to GCR irradiation [6]. These ages can be used to calibrate the relative ages of the lunar surface, as determined by the morphology of the craters [7].

In this work, we develop a Monte Carlo model, based on the Geant4 software package, to calculate the production rates of cosmogenic nuclei. Before applying this model extensively, it is necessary to test its validity. To this end, we have chosen the Apollo 15 long drill core as our research sample because its chemical composition, location, and the shielding depth of the samples are known clearly. In addition, the Apollo 15 drill core is the least disturbed sample from the three deep drill cores of Apollo 15, 16, and 17. We calculate the production rates of long-lived nuclei ^{10}Be and ^{26}Al for the Apollo 15 drill core and and compare these results with the experimental data. This paper is organized as follows: in Section 2 we describe the theoretical model, in Section 3 we discuss the numerical results, and a summary and outlook is given in Section 4.

2 The theoretical model

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

$$P_{\rm i}=\sum_{\rm k}\sum_{\rm j}N_{\rm j}\int J_{\rm k}(E,R,d)\sigma_{\rm j,k}(E){\rm d}E, \tag{1}$$

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

Before meteoroids impact the Earth's atmosphere, they are irradiated by galactic cosmic rays. In this work, we take the most abundant particles in GCRs, protons and α particles, as primary particles, which bombard the surface of meteoroids isotropically. The fluxes of protons and α particles are taken as follows [10]:

$$J_{\rm p}(E,M) = C_{\rm p}\frac{E(E+2m_{\rm p}c^2)}{(E+M)(E+M+2m_{\rm p}c^2)} \times(E+M+x_{\rm p})^{-\gamma_{\rm p}}, \tag{2}$$

$$J_{\alpha}(E,M) = C_{\alpha}\frac{E(E+2m_{\rm p}c^2)}{(E+M)(E+M+2m_{\rm p}c^2)} \times(E+M+x_{\alpha})^{-\gamma_{\alpha}}. \tag{3}$$

In these two equations, E denotes the energy per nucleon in MeV, M is the solar modulation parameter in MV, and $m_{\rm p}c^2 = 938$ MeV is the rest mass of the proton. In Eq. (2), $C_{\rm p} = 1.244\times10^6({\rm cm}^2\cdot{\rm s}\cdot{\rm MeV})^{-1}$, $x_{\rm p} = 780\ \exp(-2.5\times10^{-4}(E+M))$, and $\gamma_{\rm p} = 2.65$. In Eq. (3), $C_{\alpha}=2.23\times10^5({\rm cm}^2\cdot{\rm s}\cdot{\rm MeV})^{-1}$, $x_{\alpha}=660\exp(-1.4\times10^{-4}(E+M))$, and $\gamma_{\alpha}=2.77$. These formulae are used to generate the primary protons and α particles.

When the high energy protons and α particles bombard the meteoroid, they will interact with the atoms and nuclei therein. The dominant processes are ionization energy loss and spallation reactions. Through ionization energy loss, the energy of the primary particles will decrease continuously, while many secondary particles, such as protons, neutrons and mesons, are produced by the spallation reactions. These secondary particles will also induce reactions. In particular, the 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 protons and neutrons in the irradiated body. Monte Carlo simulation is a good choice for these calculations. Among the various Monte Carlo based software packages available, Geant4 [11] has been widely used in nuclear physics and space science [12, 13]. In our recent work [14], the fluxes of neutrons that escape from the lunar surface were investigated using the Geant4 software. In the present work we will also use this software to calculate the proton and neutron fluxes beneath the surface of a meteoroid. In order to obtain the differential fluxes of active particles, the energies of primary and secondary protons and neutrons at different depths are recorded and saved as ROOT files. We then obtain the numerical differential fluxes of different particles by analyzing the ROOT files. However, due to the statistical nature of the Monte Carlo method, there are statistical fluctuations in the fluxes. To calculate the production rates of cosmogenic nuclei by Eq. (1), it is necessary to obtain the analytical expressions for proton and neutron fluxes by the best-fit procedure. Once the analytical expressions for fluxes are obtained, one can then calculate the production rates of interesting nuclei by combining these flux formulae 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, such as the thick target irradiation experiment, because the neutron is a neutral particle that cannot 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].

We have now established a physical model to calculate the production rates of cosmogenic nuclei in an extra-terrestrial body, such as a meteoroid. However, before applying this model to extensive studies it is necessary to validate the model. To this end, we have chosen the Apollo 15 lunar drill core as our research object because its chemical composition, location, and the shielding depth of samples are clearly known. In addition, the Apollo 15 drill core is the least disturbed sample from the three deep drill cores of Apollo 15, 16 and 17 [17, 18]. In this case the radius of the Moon can be regarded as infinite, and the surface can be seen as a plane. In simulations we establish a sufficiently large box filled with the average chemical composition of the Apollo 15 drill core [19], with the GCRs incident on its upper surface. In this work, the box is taken as 100 m long ×100 m 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), are isotropically incident on the upper surface of this box. Considering both the statistical accuracy and time cost, 5 million particles are simulated.

Once the production rate is calculated, one can derive the cosmic ray exposure (CRE) age by using the following relations. For a stable cosmogenic nuclide

$$S = P_{\mathrm{s}} T, \tag{4}$$

and for a radioactive cosmogenic nuclide with the decay constant λ

$$R = P_{\mathrm{R}} \lambda^{-1} (1 - \mathrm{e}^{-\lambda T}), \tag{5}$$

where T is the CRE age, and S (R) and P_{s} (P_{R}) are the concentration and production rate of stable (radioactive) nuclides, respectively. The basic unit of the cosmogenic nuclide concentration is the number of atoms per gram sample (atoms/(g sample)). In the literature, 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

$$A = \lambda R = P_{\mathrm{R}} (1 - \mathrm{e}^{-\lambda T}). \tag{6}$$

From this equation, one can see that if the CRE age is much longer than the half-life of this nuclide, then 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 quantity. In this paper, we will choose nuclei whose half-lives are much longer than the time since the lunar core was returned from the Moon but much shorter than the CRE age. ^{10}Be ($T_{1/2}$= 1.51×10^6yr) and ^{26}Al ($T_{1/2}$=7.17×10^5 yr) are good candidates.

3 Numerical results and discussion

According to the theoretical model described in Section 2, we have written a Geant4 code to simulate the interactions of GCRs with the matter of 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. The differential fluxes for neutrons and protons at different energy ranges are then fitted. After careful analysis, we find that the proton and neutron fluxes can be expressed well by the following formulae:

$$J_{\mathrm{p}}(E,d) = \begin{cases} p_0 (E+p_1)^{p_2} E/(E+p_3), & (10 \leqslant E \leqslant 500) \\ p_0 (E+p_1)^{p_2}, & (500 \leqslant E \leqslant 10^4) \end{cases}, \tag{7}$$

$$J_{\mathrm{n}}(E,d) = \begin{cases} p_0 \mathrm{e}^{-E/p_1}, & (10 \leqslant E \leqslant 200) \\ p_0 \mathrm{e}^{-E/p_1}/(E+p_2), & (200 \leqslant E \leqslant 10^4) \end{cases}. \tag{8}$$

In these formulae the energy E is in MeV, and the p_0, p_1, p_2, and p_3 are depth and chemical dependent parameters. These formulae are much simpler than those used by Arnold [8] and Reedy [9]. The parameters are determined by a best-fit procedure using ROOT software. Due to the limits of space, we will not give the numerical results of these parameters here. 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, and the unit is g/cm^2. In this figure the fluxes are not normalized to particles/(cm^2·s·MeV) since we are interested in the relative magnitude of proton and neutron fluxes. From this figure, one can see that at high energies ($E>200$ MeV) the proton flux is larger than the neutron flux but in the lower energy range ($E<100$ MeV) the neutron flux is larger than the proton flux. This happens because the protons beneath the lunar surface include both primary and secondary particles but the neutrons are purely secondary particles. The secondary protons will suffer ionization loss and stop quickly.

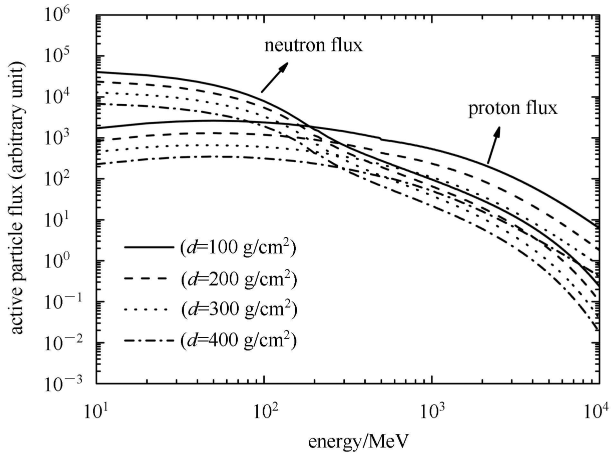

Fig. 1. The proton and neutron fluxes at depths d=100, 200, 300, 400 g/cm^2.

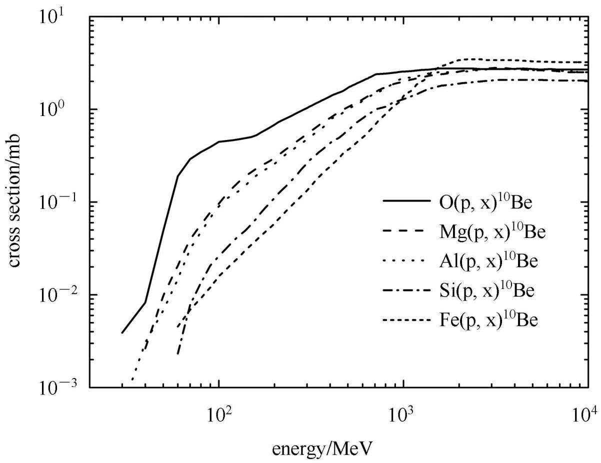

Fig. 2. The excitation function for proton induced reactions to produce ^{10}Be on target elements O, Mg, Al, Si, Fe. These data are taken from Ref. [15].

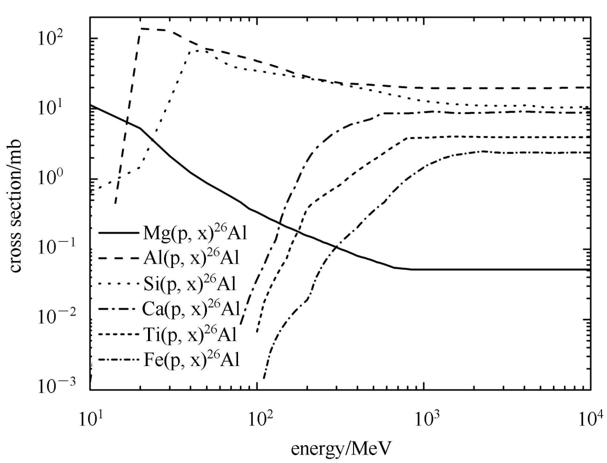

Fig. 3. The excitation function for proton induced reactions to produce ^{26}Al on target elements Mg, Al, Si, Ca, Ti, Fe. These data are taken from Ref. [15].

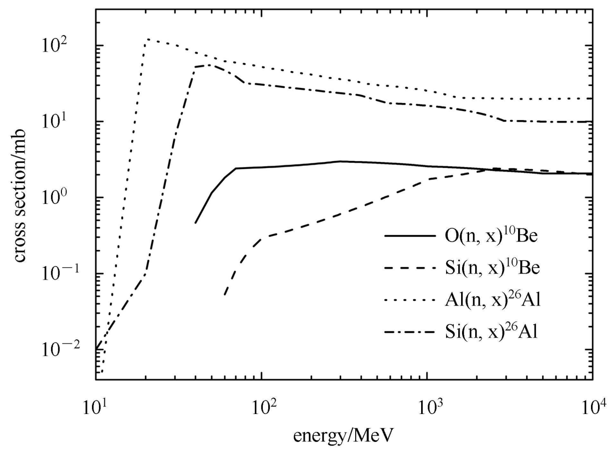

Fig. 4. The excitation function for neutron induced reactions to produce ^{10}Be on target elements O, Si, and ^{26}Al on elements Al, Si. These data are taken from Ref. [16].

For the cross sections for proton and neutron induced reactions, the latest 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.

From these figures one can clearly see that the excitation functions for these reactions are not smooth. This happens because the spallation reaction is a very complex process, so 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 the cosmogenic nuclei ^{10}Be and ^{26}Al are calculated by integrating the depth-dependent fluxes of active particles with the excitation functions of the nuclear reactions involved. By using this method, the production rates of ^{10}Be and ^{26}Al in the Apollo 15 drill core are calculated. In our calculations, the production rates resulting from proton induced reactions and neutron induced reactions are considered. For proton induced reactions, the target elements that we have considered are O, Mg, Al, Si and Fe for ^{10}Be, Al, Si, Ca and Ti, and Fe for ^{26}Al. 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 introduced two normalization factors for the production rates of neutron and proton induced reactions:

$$P_{\rm R}=C_{\rm p}P_{\rm R,p}+C_{\rm n}P_{\rm R,n}, \tag{9}$$

where $P_{\rm R}$ is the total production rate of radioactive nuclei, and $P_{\rm R,p}$ and $P_{\rm R,n}$ are the contributions due to proton and neutron induced reactions, respectively, which are calculated using the theoretical model shown in Section 2. The main reasons for introducing these factors are as follows: (1) the excitation functions are obtained by interpolating a small number of cross section data, and, in particular, the neutron cross section data are only obtained in indirect ways; (2) the secondary proton and neutron yields calculated by Geant4 depend on the theoretical model used for spallation reactions; and, (3) the spectrum of primary cosmic rays is assumed to be the current mean value averaged over the solar activity cycle. That is to say, the uncertainties in the primary GCR fluxes, secondary particle fluxes and excitation functions in the theoretical model are normalized by the two parameters $P_{\mathrm{R,p}}$ and $P_{\mathrm{R,n}}$. 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 and dashed lines 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}Be are taken from Ref. [17], and the data for ^{26}Al are taken from Ref. [18]. From these two figures one can see that the theoretical production rates of ^{10}Be and ^{26}Al agree well with the measured data. In addition, the production rates of neutron induced reactions are larger than those 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 a crucial role.

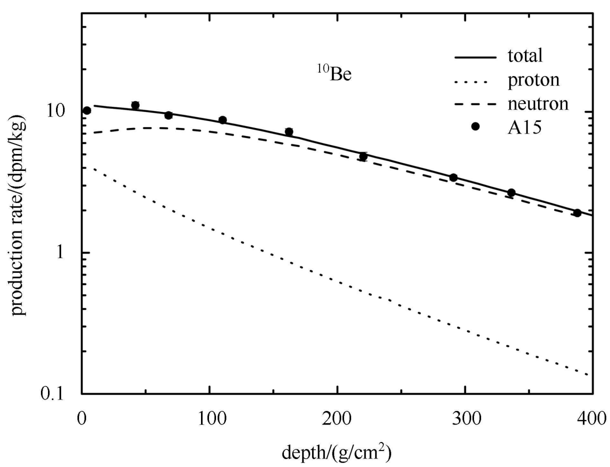

Fig. 5. The theoretical and experimental production rates of ^{10}Be in the Apollo 15 drill core. The experimental data are taken from Ref. [17].

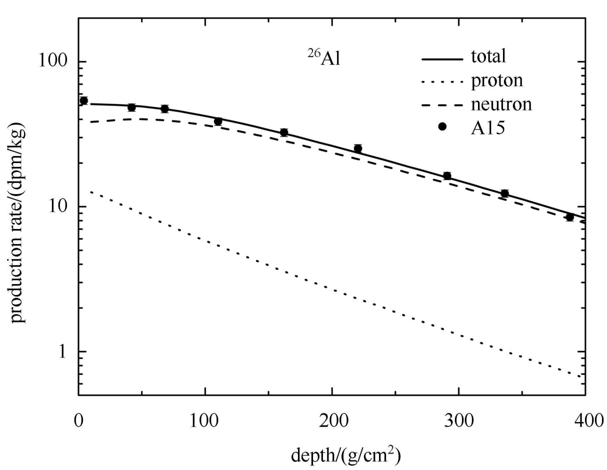

Fig. 6. The theoretical and experimental production rates of ^{26}Al in the Apollo 15 drill core. The experimental data are taken from Ref. [18].

4 Summary and outlook

In summary, a physical model based on the Monte Carlo method has been proposed to calculate the production rates of cosmogenic nuclei. A Geant4 code has been developed to simulate the interactions of primary and secondary particles with the matter in extra-terrestrial bodies. As a test of this model, we have calculated the production rates of the long-lived ^{10}Be and ^{26}Al nuclei in the Apollo 15 drill core. The information of neutrons and protons at different depths are recorded and saved as ROOT files. The neutron and proton differential fluxes are then obtained using ROOT. By combining the differential fluxes with the newly evaluated spallation cross sections, the production rates of ^{10}Be and ^{26}Al are calculated and compared with the experimental data. The results show that the theoretical production rates agree quite well with the measured data for the Apollo 15 long drill core. This means that our model is suitable to investigate the production rates of cosmogenic nuclei in extra-terrestrial bodies. It is reasonable to believe that this model can be applied to the investigation of production rates of cosmogenic nuclei in meteorites and in the Earth's atmosphere. Furthermore, based on the current schedule of the Chinese lunar exploration program, new lunar samples should be returned in about 10 years' time. When the lunar samples are obtained, the cosmic ray exposure history of the landing sites will be 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 as deduced from the counting rate of impact craters. To reach this goal, it is necessary to improve our model by using a better physical model of high energy nuclear reactions and more accurate cross sections for proton and neutron induced reactions. As to the former, we can expect that with the improvement of the nuclear reaction model, for instance the Liège intranuclear cascade (INCL) model [20], the proton and neutron spectrum calculation will become increasingly accurate. As to the latter, the neutron cross sections measured using the quasi-monoenergetic neutron beams produced by ^{7}Li(p,n) ^{7}Be reactions within the European HINDAS (High- and INtermediate-energy Data for Accelerator-driven Systems) project [21] will give us an unprecedented opportunity to study the production rates of cosmogenic nuclei.

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