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Depth dependency of neutron density produced by cosmic rays in the lunar subsurface

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Abstract

Depth dependency of neutrons produced by cosmic rays (CRs) in the lunar subsurface was estimated using the three-dimensional Monte Carlo particle and heavy ion transport simulation code, PHITS, incorporating the latest high energy nuclear data, JENDL/HE-2007. The PHITS simulations of equilibrium neutron density profiles in the lunar subsurface were compared with the measurement by Apollo 17 Lunar Neutron Probe Experiment (LNPE). Our calculations reproduced the LNPE data except for the 350–400 mg/cm^2 region under the improved condition using the CR spectra model based on the latest observations, well-tested nuclear interaction models with systematic cross section data, and JENDL/HE-2007.

Keywords: Neutron density; Cosmic rays; Lunar and planetary spectroscopy; Moon; PHITS; High energy nuclear data

1. Introduction

The lunar surface is exposed to cosmic rays (CRs) all the time due to the extremely thin atmosphere and the very weak magnetic field. Initiated by the nuclear interactions of CR nuclear components with materials in the lunar subsurface, secondary CR components such as protons, neutrons and gamma-rays are continuously generated down to a few meters below the lunar surface, and some of them are emitted into the space. The gamma-rays emitted from the lunar surface carry particularly important information on the chemical composition of the lunar subsurface with their characteristic energy spectra, and fast neutrons produced through various nuclear reactions in the lunar subsurface play an important role for the production of those gamma-rays. Measurements of the gamma-ray spectra, therefore, provide powerful information to understand the origin and evolution of the Moon (Evans et al., 1993). The gamma-ray observations with orbiter satellites have been continuously performed in many lunar science

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missions such as Lunar Prospector, Kaguya, Chang'E-1, 2 and Chandrayaan-1 over the past few decades since the end of manned missions such as the Apollo experiments (Gasnault et al., 2000; Lawrence et al., 2004; Hasebe et al., 2008, 2009; Zhu et al., 2010; Goswami et al., 2005).

Recently, the accurate understanding of the energy spectra of the secondary products at the lunar surface and subsurface has increased its importance also from the point of view of dosimetry on the Moon. Enhanced interests in the utilization of the Moon for scientific and human activity have led to various estimations of radiation environment on the ground and underground of the lunar surface (Reedy and Arnold, 1972; McKinney et al., 2006). Highly advanced simulation techniques of radiation transport in matter have made it possible to calculate the dose against human health to which contributed by primary and secondary components of CRs and solar energetic particles (SEPs) assuming various situations (Adams et al., 2007; Hayatsu et al., 2008). However, in doing such simulation, there still remain many uncertainties resulting from the limited knowledge of the physical environment on the Moon such as CR flux, chemical abundance, density of the lunar material, and the limited accuracy of nuclear reaction models and evaluated nuclear data. Thus, discrepancies between the calculated and measured results have been found (e.g., Reedy and Arnold, 1972; McKinney et al., 2006; Adams et al., 2007; Hayatsu et al., 2008).

From such background, we worked on verification of a simulation technique through an estimation of the depth dependency of the neutron spectra in the lunar subsurface in this work. The neutrons play the key role for the subsequent production of gamma-rays (Feldman et al., 1993) and account for approximately 8% of dose contribution (Hayatsu et al., 2008). Also, the neutron density as a function of depth (profile) had been measured by Lunar Neutron Probe Experiment (LNPE) as a part of Apollo 17 missions with detailed information of chemical composition of the soil at the measured point (Woolum et al., 1973, 1975; Woolum and Burnett, 1974a, 1974b; Carrier, 1974; Mitchell et al., 1974). Thus, the estimation of the neutron density profile will be appropriate for benchmarking our simulation method among the obtainable data at present. We have performed our calculations with the three-dimensional Monte Carlo code, PHITS (Nara et al., 2000; Niita et al., 1995, 2010; Iwase et al., 2002; Sihver et al., 2010). In our recent paper (Ota et al., 2011) in which we succeeded in reproducing the measurement by the LNPE with the PHITS, there remained ambiguities in our calculation, which resulted from two simulation conditions, i.e., the CR spectra when the LNPE was performed and the accuracy of nuclear reaction models. We have improved these two conditions in this work by benchmarking with the latest observed CR data and systematically measured nuclear reaction cross section data set.

In the latest versions of PHITS, the evaluated high energy nuclear data, JENDL/HE-2007 (Fukahori et al., 2002) has been extended to 3 GeV for proton and neutron reaction. We also tested its validity in our calculations. This paper presents our calculations of the neutron density profile produced by the CRs in the lunar subsurface under those improved conditions and discusses the future application of our simulation method for lunar and planetary science and space dosimetry.

2. Simulation procedure

2.1. Lunar neutron probe experiment

The Lunar Neutron Probe Experiment (LNPE) measured the equilibrium (thermal) neutron ($5\,\mathrm{meV} < E < 500\,\mathrm{eV}$) density profile in the lunar subsurface (to a few meters below the surface) via $^{10}B(n,\alpha)^7\mathrm{Li}$ reaction using cellulose triacetate plastic detectors to which ^{10}B targets are attached as a part of the Apollo (AP) 17 missions in 1972 (Woolum et al., 1973, 1975; Woolum and Burnett, 1974a, 1974b). The simulation condition was set to the actual one under which the LNPE was performed. Since the planet being modeled is well represented by a sphere and a sphere is the most efficient transport boundary to differentiate the chemical compositions depending on depth, a sphere with the radius of 1738 km (the same size as the Moon) was modeled as the target McKinney et al. (2006). Then, three concentric spheres were configured inside the lunar body to simulate the differences of materials and densities dependent on the depth below the surface. The materials and densities in the lunar body were determined from the data given by McKinney et al. (2006). Their data are given based on the measurements by the Soil Mechanics experiment (Carrier, 1974; Mitchell et al., 1974) which was also performed as one of the AP17 missions at almost the same site as the LNPE. Common characteristics in four depth regions are (a) elemental abundance of 40 wt% O, 20 wt% Si, and 12 wt% Fe plus small number of Na, Mg, Al, K, Ca, Ti, Cr, Mn, and a fraction of Sm, Eu, Gd, and Th, and (b) density of about $2\,\mathrm{g/cm^3}$. Each region has slight differences in the fraction of elemental abundances and densities (1.76–$2.11\,\mathrm{g/cm^3}$). Readers can find the detailed values of the abundances in Ota et al. (2011).

An important note relevant to the LNPE measurement is that it indicates an experimental error of 16% (e.g., $(9.2 \pm 1.5) \times 10^{-6}\,\mathrm{neutrons/cm^3}$ at $150\,\mathrm{g/cm^2}$) which includes errors of track measurements (approximately 9%) and several correction effects for conversion to neutron densities, and a possible systematic uncertainty of 30% at maximum (±15%) which might have resulted from the different observer-dependent criteria for nuclear track recognition (Woolum et al., 1975). This total uncertainty (±15% (sys.) ±16% (meas.)) allows for various ambiguities in estimations (Ota et al., 2011). Hence, it is very important to carefully benchmark some significant conditions to make the best calculation.