Cosmic-ray Transport Simulation in the Atmosphere

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Abstract

Estimation of cosmic-ray neutron spectra in the atmosphere has been an essential issue in the evaluation of the aircrew doses and the soft-error rates of semiconductor devices. We therefore performed Monte Carlo simulations for estimating neutron spectra, using the PHITS code coupled with the nuclear data library JENDL-High-Energy (JENDL/HE) file or the intra-nuclear cascade (INC) model for simulating high-energy neutron and proton induced nuclear reactions. The calculated spectra based on JENDL/HE agree with measured data very much for a wide altitude range even at ground level. On the other hand, the calculation adopting INC generally overestimates the measured data, especially at lower altitudes. These tendencies indicate that JENDL/HE can play an important role not only in the cosmic-ray transport simulation, but also in the deep-penetration simulation for the shielding design of high-energy accelerator facilities, since the two simulations have a lot of similarities with respect to the source terms, shielding properties and so on. The incorporation of the pion-production channels into JENDL/HE will be very helpful in the future study of radiation protection dosimetry.

1. Introduction

In the last decade, radiation protection for aircrews against terrestrial cosmic-rays was one of the most intensively discussed dosimetric issues. Furthermore, increasing attention has been paid to the soft errors of semiconductor devices induced by the cosmic-rays even at the ground level, since the recent miniaturization of the devices causes a rapid decrease of their critical charges. These radiation effects are predominantly triggered by neutrons produced by nuclear reactions between the cosmic-rays and atmospheric components. Therefore, estimation of cosmic-ray neutron spectra in the atmosphere is an essential issue in the evaluation of the aircrew doses and the soft-error rates (SERs).

A number of studies have been devoted to the estimation of the neutron spectra[1-4)] by performing atmospheric propagation simulations of cosmic-rays. However, the cosmic-ray neutron spectra depend not only on the atmospheric depth, cut off rigidity and solar modulation (referred to here as global conditions) but also the structure of the aircraft[5)] and the water density around the point of interest[2)] (referred to here as local geometries) in an intricate manner, and none of the existing models are able to reproduce the measured neutron spectra at any location and time with satisfactory accuracy. One reason for causing the difficulty in reproducing the measured data is that the atmospheric propagation simulation of cosmic-rays requires a very sophisticated nuclear reaction model for high-energy neutrons, since the atmosphere is very thick, approximately 1000 g/cm^2, and even a slight inaccuracy in the calculated transparency of high-energy neutrons triggers a huge discrepancy of the neutron spectra at the end of the atmosphere *i.e.* sea level. For instance, it is known that the simulation employing a widely-used nuclear reaction model of the intra-nuclear cascade[6)] (abbreviated to INC, hereafter) generally overestimates the cosmic-ray neutron spectra at sea level.

With these situations in mind, we have calculated the cosmic-ray neutron spectra by performing Monte Carlo particle transport simulation in the atmosphere based on the Particle and Heavy Ion Transport code System PHITS[7,8)], utilizing the latest version of the nuclear data library JENDL-High-Energy File[9,10)] (abbreviated to JENDL/HE, hereafter). Similar simulation but employing INC instead of JENDL/HE was also performed in order to figure out the dependence of the cosmic-ray neutron spectra on the nuclear reaction model. Based on a comprehensive analysis of the simulation results, we proposed analytical functions to predict the cosmic-ray neutron spectra at any global condition at the altitudes below 20 km, considering the local geometry effect.

The details of the calculated results together with the derivation and verification of the analytical function had already been reported in our previous paper[11)]. Hence, this paper focuses on the discussion about the role of the nuclear reaction models in the atmospheric-propagation simulation of cosmic-rays by comparing between the neutron spectra obtained by the simulations employing JENDL/HE and INC.

2. Simulation Procedure

The earth system virtually constructed in our simulation is depicted in Figure 1. The earth was represented as a sphere with the radius of 6378.14 km, and its composition was assumed to be 59.2% oxygen, 28.0% silicon, 10.6% aluminum and 2.2% hydrogen by mass. This constitution corresponds to 60% SiO_2, 20% Al_2O_3 and 20% H_2O by mass. The particles arriving at 1000 g/cm^2 below the ground level were discarded in the simulation for reducing the computational time, since there are few albedo neutrons from so deep underground to the atmosphere. The atmosphere was divided into 28 concentric spherical shells, and its maximum altitude was 86 km. The densities and temperatures of each shell were determined referring to the US-Standard-Atmosphere-1976. The atmosphere was assumed to be composed of 75.4% nitrogen, 23.3% oxygen and 1.3% argon by mass above the altitude of 2 km, and additionally, 0.06% hydrogen by mass below this altitude due to the existence of water vapor. Note that argon was replaced by the atom with the same mass number – calcium – in our simulation, since JENDL/HE does not yet include the data for argon.

In the simulation, cosmic-rays were incident on the earth system from the top of the atmosphere, *i.e.* from the altitude of 86 km. Proton, alpha and heavy ions with charges up to 28 (Ni) were considered as the source particles, although the contributions of heavy ions to the cosmic-ray neutron spectra are generally small. The incident cosmic-ray spectra for the 30 conditions – 15 geomagnetic fields with the vertical cut-off rigidities from 0.1 to 14 GV at the solar minimum and solar maximum periods, respectively – were considered in our simulation, and the spectra were calculated by the CREME96 code[12)].

The atmospheric propagation of the incident cosmic-rays and their associated cascades was simulated by the PHITS code, which can deal with the transports of all kinds of hadrons and heavy ions with energies up to 200 GeV/n. As mentioned before, the simulation was performed alternatively by employing JENDL/HE or INC for high-energy neutron and proton induced nuclear reactions. The reaction models adopted in each simulation are summarized in Figure 2. Note that the pion-production channels are excluded from the database of JENDL/HE used in the PHITS simulation, and hence, the transports of pions and the associated particles with their decay – muon, photon, electron and positron – were not considered in our simulation.

3. Results and Discussion

Figure 3 shows the comparisons of the calculated neutron spectra with the corresponding experimental data obtained by Goldhagen *et al.*[13)] and Nakamura *et al.*[14)]. The statistical errors in the values obtained by the simulation are generally small – approximately less than 5% and 20% for the high altitude and ground level data, respectively, except for very high and low energies. The spectra predicted by the analytical functions based on the JENDL/HE data, which were proposed in our previous paper[11)], are also plotted in the figures.

Two peaks around 1 MeV and 100 MeV can be observed in every spectrum. The former is attributed to neutrons emitted by the evaporation process, while the latter is to those produced by the pre-equilibrium and intra-nuclear cascade processes. The peaks at the thermal energy can be found only in the spectra at the ground level, since they are predominantly composed of the earth's albedo neutrons.

It is evident from the figure that the simulation employing JENDL/HE can reproduce the experimental data for all the calculated conditions very well. On the other hand, the simulation adopting INC generally overestimates the measured data, especially for lower altitudes. This discrepancy is predominantly attributed to the tendency of INC to over-predict the yields of high energy secondary particles knocked out by nuclear reactions of light nuclei such as nitrogen and oxygen. As an example to show the difference between JENDL/HE and INC, the neutron and proton spectra produced from the 150 MeV neutron-induced nuclear reaction of oxygen calculated by the two models are plotted in Figure 4. It is obvious from the figure that INC gives larger values for both the neutron and proton yields at high energies than JENDL/HE does. This tendency causes the over-prediction of neutron fluences in deep-penetration calculations such as the cosmic-ray propagation simulation in the atmosphere.

It is also found from Fig. 3 that the analytical functions are substantially superior to the Monte Carlo simulation in reproducing experimental data at lower energies, although they were proposed based on the simulation data obtained by PHITS coupled with JENDL/HE. This is because the local geometry effect on the spectra is precisely considered in the analytical calculation, providing the water density in ground or the mass of aircraft to the functions. Using the analytical functions, we have developed EXcel-based Program for Calculating Cosmic-ray Spectrum (EXPACS), which can calculate not only cosmic-ray neutron spectrum but also the corresponding effective dose and ambient dose equivalent for any locations in the world. The software has been opened for public from its web site[15)].

4. Conclusions

The cosmic-ray neutron spectra were calculated by performing the atmospheric-propagation simulation by the PHITS code coupled with JENDL/HE or INC. The calculated spectra based on JENDL/HE agree with measured data very much for a wide altitude range even at ground level. On the other hand, the calculation adopting INC generally overestimates the measured data, especially at lower altitudes. These tendencies indicate that JENDL/HE can play an important role not only in the cosmic-ray transport simulation, but also in the deep-penetration simulation for the shielding design of high-energy accelerator facilities, since the two simulations have a lot of similarities with respect to the source terms, shielding properties and so on. In the future, we plan to calculate the photon and charged-particle spectra in the atmosphere, applying the Monte Carlo simulation technique established by this work.

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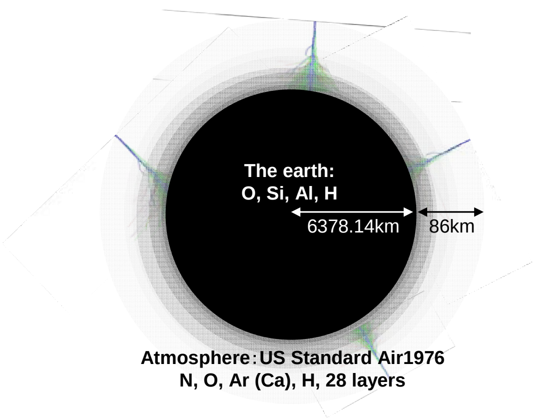

Figure 1 Earth system virtually constructed for the atmospheric-propagation simulation of cosmic-rays

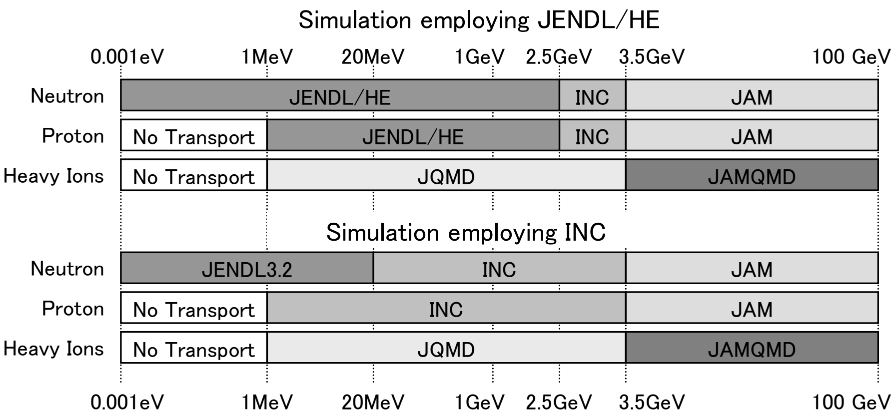

Figure 2 Nuclear reaction models employed in the atmospheric-propagation simulation of cosmic-rays

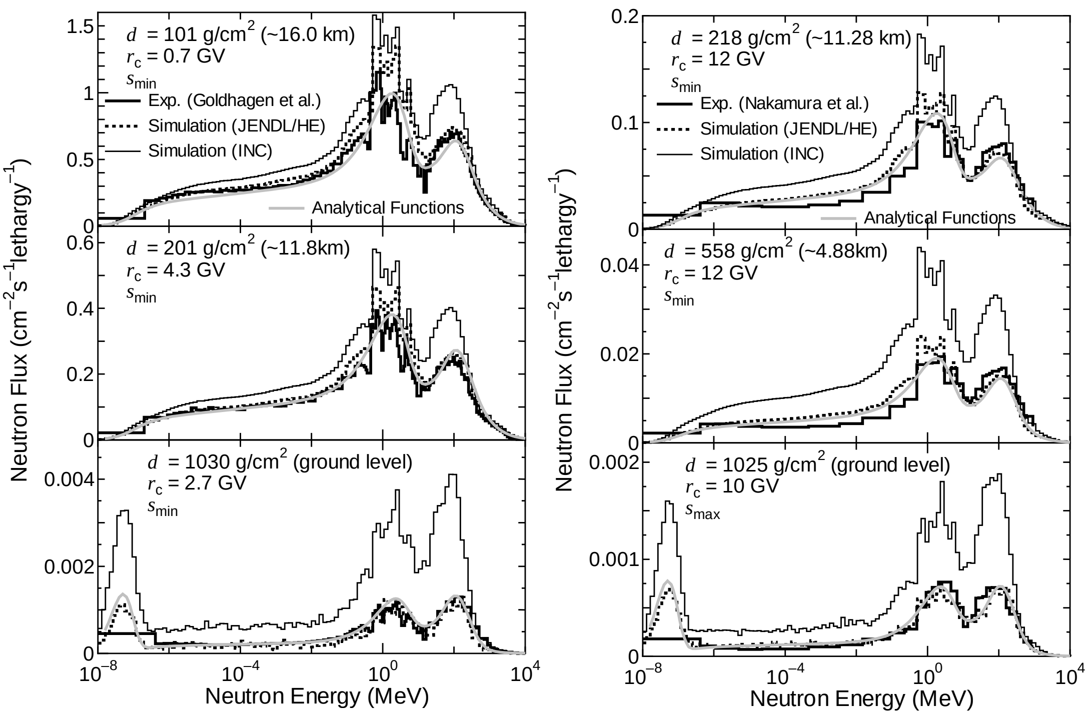

Figure 3 Calculated and measured neutron spectra in the atmosphere. The values of d and r_c are the atmospheric depth and the cut-off rigidity, respectively, while s_{min} and s_{max} indicate the solar minimum and maximum, respectively.

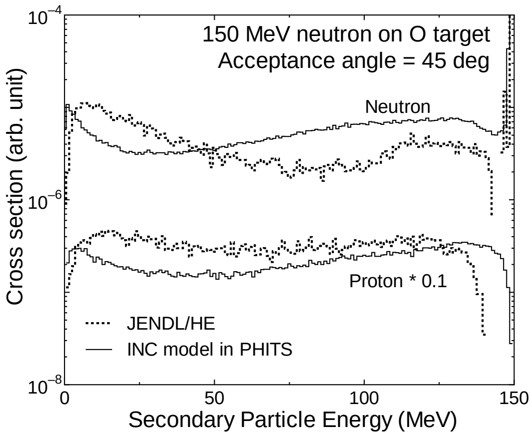

Figure 4 Neutron and proton spectra produced from the 150 MeV neutron-induced nuclear reaction of oxygen calculated by JENDL/HE and the INC model implemented in PHITS.