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Title: MCNP6 Cosmic & Terrestrial Background Particle Fluxes - Release 3

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MCNP6 Cosmic & Terrestrial Background Particle Fluxes – Release 3

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INTRODUCTION

The galactic cosmic-ray (GCR) source option[1] was implemented in the all-energy, all-particle transport code MCNP6[2] in 2010. Earlier this year, we reported on Release 2 of the MCNP6 cosmic and terrestrial background flux file (background.dat).[3] In this paper, we report on enhancements that have been made to the modeling and simulation of these spectra, identified as Release 3 of the background.dat file, which is read and sampled by MCNP6 whenever a user invokes the background source option.

Cosmic radiation continuously bombards Earth with various particles, such as protons, α particles, and heavier nuclei, some of which are deflected by the Earth's shielding magnetic field. Particles that carry sufficient momentum can overcome the deflection and penetrate into the atmosphere. The sufficient momentum is dependent on the terrestrial coordinates due to the shape of the Earth's magnetic field and the Lorentz force's proportionality to the sine of the angle between the velocity vector of the incoming particle and the magnetic field direction.

As the particles propagate through the atmosphere, collisions with atmospheric molecules generate secondary particles such as neutrons, protons, photons, muons, pions, and other exotic particles. These secondary particles often have sufficient energy to undergo additional nuclear interactions, and so on, forming what is known as a cascade shower.

The tabulation of background particle fluxes on the surface of the earth is important for a variety of reasons, one of which is the design of nuclear material detection systems.

DESCRIPTION OF THE ACTUAL WORK

The simulations reported here used various models and formulations for the cosmic source spectra, atmosphere, and terrestrial conditions to correctly model the propagation of GCR particles through the atmosphere to surface level.

Cosmic Source Spectra

MCNP6 provides two different formulations of GCR spectra: an older formulation, referred to as LEC (Lal with Energy Cutoffs), proposed by the Physical Research Laboratory (Ahmedabad, India),[4] and a modern formulation developed at the Bartol Research Institute (BRI, University of Delaware, Newark, DE)[5] in 2004. Details about these cosmic spectra can be found in our earlier paper.[3] Whenever a user specifies a terrestrial location (via the LOC keyword on the SDEF card), the BRI formulation is invoked, providing automatic normalization of the source and Monte Carlo sampling of light and heavy GCR (although in the current version of MCNP6 only protons and alphas are utilized).

MCNP6 models solar modulation by interpolation of measured data (1965-2005) or parameterized data (for years outside the range), using a specified date (via the DAT keyword on the SDEF card) and a standard formulation.[6] It models geomagnetic modulation by truncating the energy sampling spectrum of protons and α particles in accordance to the BRI rigidity cutoff as previously described. Other similar formulations can be found in the literature.[7,8]

Atmosphere Model

These simulations modeled the atmosphere as a rectangular prism protruding from 2 meters below sea level up to 65 km in altitude with a base of 200 m by 200 m. The prism was segmented horizontally into 300 cells to account for the varying atmospheric conditions (temperature, pressure, air composition). This optimal number of horizontal cells was determined by comparing results across a wide range of segment sizes. Temperature (T) and pressure (p) altitude profiles were taken from the U.S. Standard Atmosphere:[9]

$$T = T_0 - L\,h$$
$$p = p_0\,(1 - L\,h / T_0)^{g\,M/(R\,L)},$$

with the parameters described in Table I.

Table I. Definitions of Atmosphere Variables

Physical Quantity	*Value*
Sea Level Temperature, T_0	288.15 K
Sea Level Pressure, p_0	$1.01325*10^5$ Pa
Temperature Lapse Rate, L	.0065 K/m (altitude dependent)
Altitude, h	
Air Molar Mass, M	28.9644 g/mol
Gravity, g	9.80665 m/s^2
Gas Constant, R	8.315 J/(K mol)

Atmospheric density was computed from the Ideal Gas Law,

$$\rho = p\,M / (R\,T).$$

Air composition was defined by the standard fractions for high atmosphere (n_N = .78 for nitrogen, n_o =.21 for oxygen, and n_{Ar} =.01 for argon), and allowed to contain water vapor near the ground according to a specified relative humidity (RH). The hydrogen fraction content of air was determined by

$$n_{H2O} = RH\, p_s / p,$$

where p_s is the saturated vapor pressure given by the Arden-Buck equation (p_s in Pa and T in ^{o}K),

$$p_s = 611.21\, e^{((19.843-T/234.5)(T-273.15)/(T-16.01))}.$$

This result is then normalized by dividing over the sum of total elemental fractions to give the hydrogen atomic fraction, or

$$A_H = 2n_{H2O}/(2n_O + n_{Ar} + 2n_N + 3n_{H2O}).$$

A_H is multiplied by the atomic mass of hydrogen and once again normalized to give the final mass fraction. The oxygen fraction increases modestly from the humidity,

$$A_O = (2n_O + n_{H2O})/(2n_O + n_{Ar} + 2n_N + 3n_{H2O}).$$

However, initial results indicate that relative humidity does not have a significant impact on the ground-level neutron flux, and subsequent simulations were all set to a relative humidity of 50% (see Fig. 1). The average temperature at a terrestrial location[10] was incorporated into the atmospheric conditions by altering the density, temperature profiles, and air compositions.

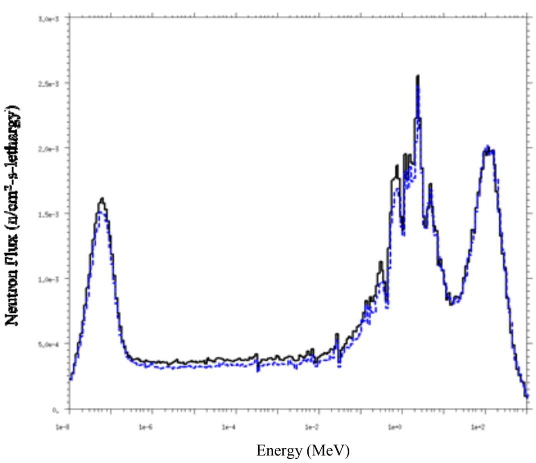

Fig. 1. Neutron lethargy plot for RH=20% (black) and RH=80% (blue), indicating a negligible dependence on relative humidity.

Sea and Ground Models

Similarly, varying ground compositions did not lead to significant changes in the ground-level neutron flux (see Fig. 2), and therefore the ground across all the simulations was taken to be nominal soil (see Table II[11]). The elevation at a specific terrestrial location was taken into consideration by having the ground cell go from 2 meters below sea level to the terrestrial location's elevation. The atmospheric cells would then follow above that. The terrestrial elevation was obtained using Google Maps' Find Altitude feature.[12]

Cases over the ocean were modeled with standard sea water composition (see Table III). In these cases, the sea water cell went from 2 meters below sea level to sea level.

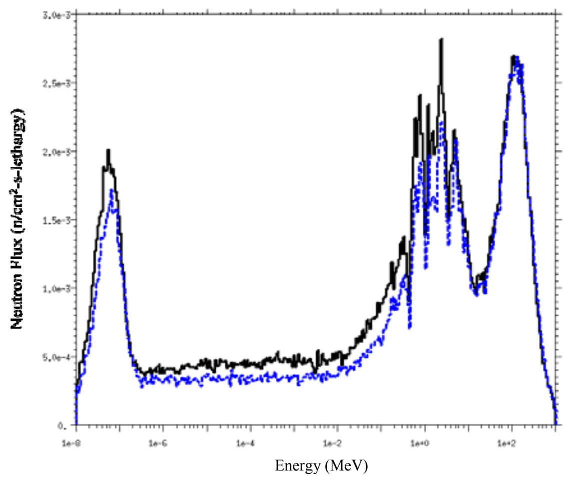

Fig. 2. Neutron Lethargy plot for various ground compositions. The dry dense and dry porous cases, which differ only in density, resulted in the black curve, while the wet dense and wet porous cases resulted in the blue curve. These variations are fairly small so a mixture of these was used (i.e., nominal soil).

Table II. Nominal Soil Composition

	Nominal
Porosity[a]	0.5
Free water content[b]	0.2
Bound water content[c]	0.05
Mineral density (g/cm^3)[d]	2.684
In situ density (g/cm^3)	1.6104
Element	
Hydrogen	0.02331[e]
Oxygen	0.55921
Silicon	0.22259
Aluminum	0.06528
Iron	0.04015
Calcium	0.02915
Potassium	0.02080
Sodium	0.02272
Magnesium	0.01678

a – *Fraction of total volume occupied by water and air*
b – *Ratio of free water to mineral mass*
c – *Ratio of bound water to mineral mass*
d – *Mineral density includes bound water*
e – *Mass fractions*

Table III. Sea Water Composition (ρ=1.027 g/cm^3)

Element	***Mass Fraction***
Hydrogen	0.108211146
Carbon	2.80029×10^{-5}
Oxygen	0.858488424
Chlorine	0.019401998
Sodium	0.010801113
Magnesium	0.001292133
Sulfur	0.000910094
Carbon	0.000400041
Potassium	0.000400041
Bromine	6.70069×10^{-5}

Simulation Details

The GCR source was positioned at the top of the atmosphere (65 km) and was specified to produce particles with velocity vectors that have a cosine-squared distribution relative to the surface normal. Reflecting boundaries were specified at the vertical walls of the prism to simulate particles coming in through the atmosphere at off angles. The date was specified on the DAT keyword as 9/1/2012.

The MODE card included nucleons (n, q, h, g), light ions (d, t, s, a), pions (z, /), kaons (k), photons (p), and muons (|). At this point in time, MCNP6 would not reliably transport the negative pions (*), negative kaons (?), or positive muons (!), but these have minimal impact on the cosmic neutron and gamma spectra. An upper energy cutoff of 1 TeV/n was used, along with the default CEM and LAQGSM physics modules (see the LCA card).

The cosmic particle flux was computed at 1262 terrestrial locations, every 5^{o} in latitude (90^{o}N, 85^{o}N, 80^{o}N, …) and 10^{o} in longitude (180^{o}W, 170^{o}W, 160^{o}W, …). The simulations ran ten million GCR incoming particles for each terrestrial location. The photon and neutron flux across the lowest air cell, from ground level to 2 meters above ground, was tallied and properly normalized. The terrestrial sea water gamma flux was computed for a single composition of water, while the terrestrial soil gamma flux was computed for all grid locations within the continental U.S. (22 grid points).

RESULTS

The MCNP6 Beta 3 GCR simulations were benchmarked by comparing the ground-level neutron flux of the nearest grid-point (40^{o}N 120^{o}W), adjusted to the proper date and elevation, to measured data taken in 2006 at SNLL, Livermore, CA.[13] As one can see in Fig. 3, the simulation results have a spectral shape that is very similar to the measured data, but are ~25% high due to several significant approximations (omission of B-field effects in the atmosphere, omission of buildings and structural materials, and use of an average temperature and pressure). An example MCNP6 terrestrial NORM simulation is presented in Fig. 4, for a representative abundance of typical radionuclides within the nominal soil and sea water.

The 1262 cosmic simulations provided ground/sea-level flux spectra for neutrons and photons at each terrestrial location. Fig. 5 and Fig. 6 indicate the variation in these spectra for various locations on Earth. In general, these spectra scale most significantly with elevation (i.e., increase with higher elevation) and less significantly with latitude (i.e., increase toward the equator – at least within the U.S.).

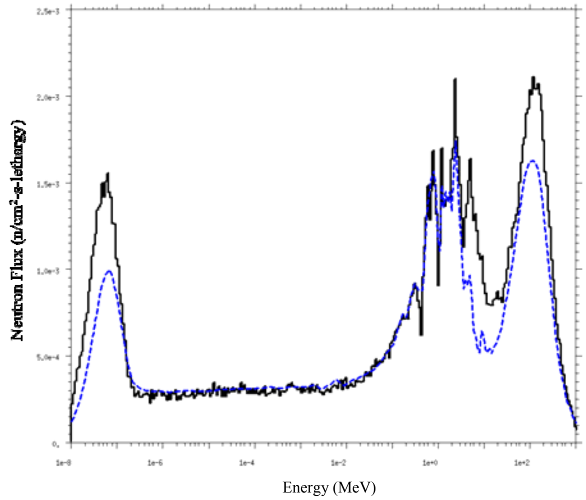

Fig. 3. Simulated (black) and measured (blue) neutron flux spectra for Nov. 6, 2006 at SNLL (37^{o}N, 122^{o}W), Livermore, CA.

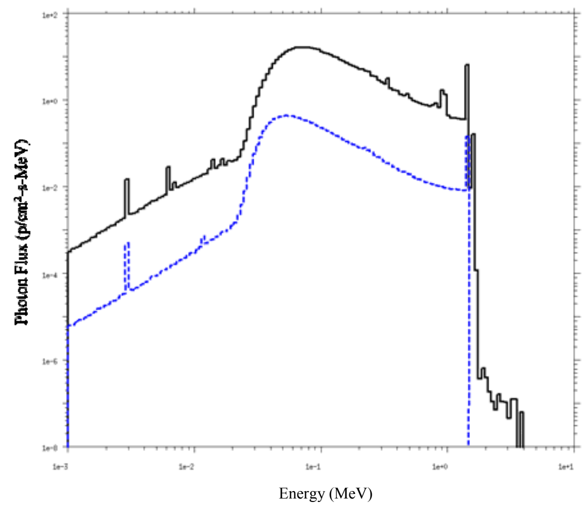

Fig. 4. Soil (black) and water (blue) NORM gamma flux spectra for a U.S. location (2 ppm ^{40}K, 5 ppm ^{232}Th, and 2 ppm ^{238}U) and nominal seawater (50 ppb ^{40}K).

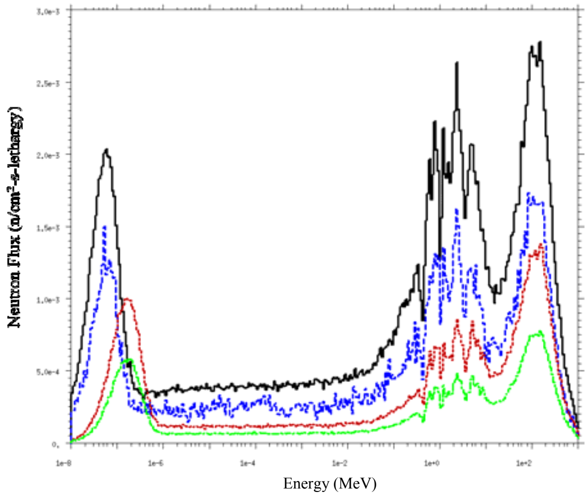

Fig. 5. Neutron spectra for southern California (black, 35°N 120°W, elevation 2000 feet), north of Toronto Canada (blue, 45°N 80°W, elevation 1000 feet), on the Atlantic Ocean (red, 35°N 40°W), and near Hawaii (green, 20°N 160°W).

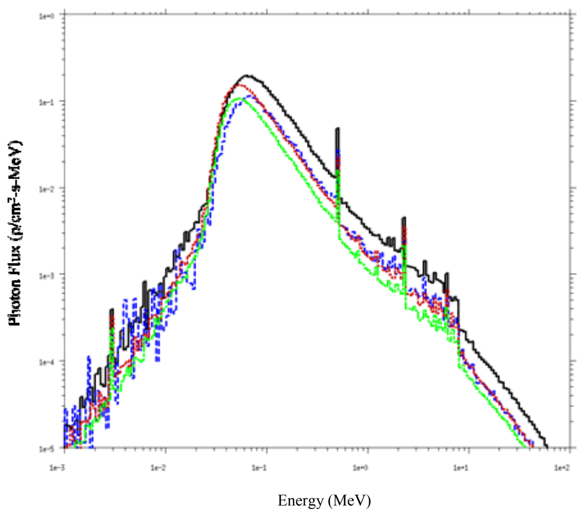

Fig. 6. Photon differential spectra for the locations specified in Fig. 5.

CONCLUSIONS

MCNP6 was used to produce ground/sea-level neutron and photon cosmic and terrestrial background fluxes on a terrestrial grid around the earth. These spectra have been incorporated into Release 3 of the "background.dat" file which will be included with the second Production Version of MCNP6 (scheduled for release in 2014). Although the statistical uncertainty of these simulated spectra are a bit high (~10%) in the Release 3 data, future releases will include a reduction in the statistical errors, a refinement in the geographic gridding, an atmospheric B-field treatment, and inclusion of heavy ions in the cosmic source.

ENDNOTES

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