MCNP6 Cosmic-Source Option

G. W. McKinney[1], H. J. Armstrong[1], M. R. James[1], J. M. Clem[2], and P. Goldhagen[3]

(1) Los Alamos National Laboratory, P.O. Box 1663 MS C921, Los Alamos, NM, 87545; gwm@lanl.gov
(2) Bartol Research Institute, University of Delaware, Newark, DE, 19716; clem@bartol.udel.edu
(3) National Urban Security Technology Laboratory, 201 Varick St., New York, NY, 10014; paul.goldhagen@hq.dhs.gov

INTRODUCTION

MCNP is a Monte Carlo radiation transport code that has been under development for over half a century. Over the last decade, the development team of a high-energy offshoot of MCNP, called MCNPX, has implemented several physics and algorithm improvements important for modeling galactic cosmic-ray (GCR) interactions with matter [1-3]. In this paper, we discuss the latest of these improvements, a new Cosmic-Source option, that has been implemented in MCNP6 [4].

DESCRIPTION OF THE ACTUAL WORK

It has been possible to model a realistic GCR source (i.e., mixed proton and alpha particles) in MCNPX since the release of version 2.5.0 in April of 2005. However, users had to be very meticulous in order to achieve the correct normalization and to properly account for solar and/or terrestrial modulation(s). With the recent development of the MCNP6 Cosmic-Source option, these concerns have been alleviated by providing automatic source normalization, solar modulation, and geomagnetic rigidity truncation of GCR spectra. This source option greatly facilitates the modeling of numerous radiation transport applications, ranging from planetary science, to exo/endo-atmospheric space effects, to terrestrial cosmic backgrounds. Details regarding these improvements are provided in the following source, user-interface, and physics sections.

Cosmic Source Spectra

The new MCNP6 Cosmic-Source option includes two fundamentally different formulations of the cosmic spectra: (1) a historical interplanetary formulation first proposed by the Physical Research Laboratory (Ahmedabad, India) [5], and (2) a modern terrestrial formulation developed at the Bartol Research Institute (University of Delaware, Newark, DE) [6]. Both of these are briefly described in the following paragraphs.

The historical interplanetary formulation, presented by Lal in 1980, will be referred to here as the Lal with energy cutoffs (LEC) option. The analytic form for the differential 4π GCR flux spectrum, as prescribed by Lal and later corrected by Masarik and Reedy [7], is given by

$$g(T,\phi) = A\ T\ (T+2E_0)\ (T+m+\phi)^{-\gamma} / [(T+\phi)\ (T+2E_0+\phi)] \quad (1)$$

where $g(T,\phi)$ has units of particles/cm^2-s-MeV, T (MeV) is the particle kinetic energy per nucleon, ϕ (MV) is the solar modulation potential, E_0 (MeV) is the rest energy of a nucleon, m=a exp(-bT), and the remaining parameters are provided in Table I.

Table I – Parameters for the differential flux equation, taken from Lal [8].

Particle	A	a (MeV)	b (MeV^{-1})	γ
Proton	1.24e6	780	2.5e-4	2.65
Alpha	2.26e5	660	1.4e-4	2.77

The solar modulation potential [5] is determined by interpolation of measured data (1965-2005) or parameterized data (for years outside this range), using a specified date (see the DAT keyword below). This modulation potential varies from ~300 MV for solar minimum to ~1400 MV for solar maximum. When a cosmic source is specified at a terrestrial location (see the LOC keyword below), the LEC proton and alpha spectra are truncated at an energy that corresponds to the Clem rigidity cutoff described in the following paragraph.

The modern terrestrial formulation, presented by Clem in 2004 [6], uses evaluated "sky-maps" that describe spatial (longitude, latitude, altitude) and angular (polar, azimuthal) dependence of GCR rigidity cutoff values. This source option links to a Fortran code, developed by the Bartol Research Institute (BRI), that provides Monte Carlo sampling of built-in primary spectra folded with rigidity cutoff distributions. While this code provides spectra for both light and heavy ions, MCNP6 currently accepts only the light ions (protons and ^{4}He ions). As described above for the LEC spectra, the solar modulation is provided as input into the BRI cosmic-source code.

Fig. 1 presents a comparison of the LEC and BRI 2π spectra at solar minimum for a few different latitudes (at 120°W). Similarly, Fig. 2 gives the LEC and BRI spectra at solar maximum. Other than a notable difference in the low-energy alpha flux, which effect spectra primarily in the polar regions, these spectra are in good agreement.

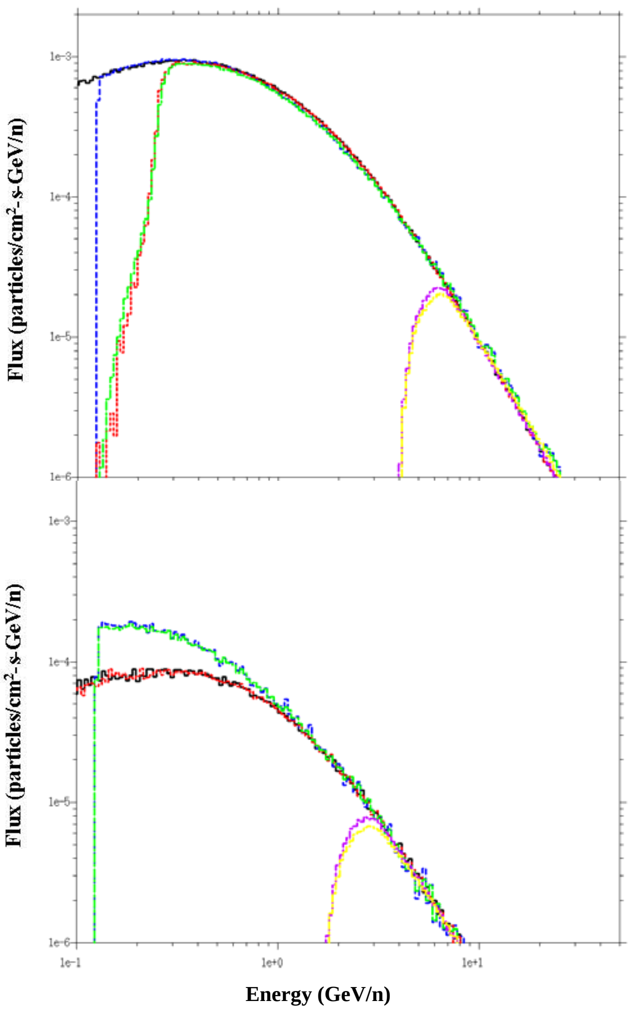

Fig. 1. Top figure gives the proton spectra for solar max. (1987) at 80°N (black=LEC, blue=BRI), 53°N (red=LEC, green=BRI), and 32°N (purple=LEC, yellow=BRI). Bottom figure gives the related alpha spectra at 80°N (black=LEC, blue=BRI), 53°N (red=LEC, green=BRI), and 32°N (purple=LEC, yellow=BRI).

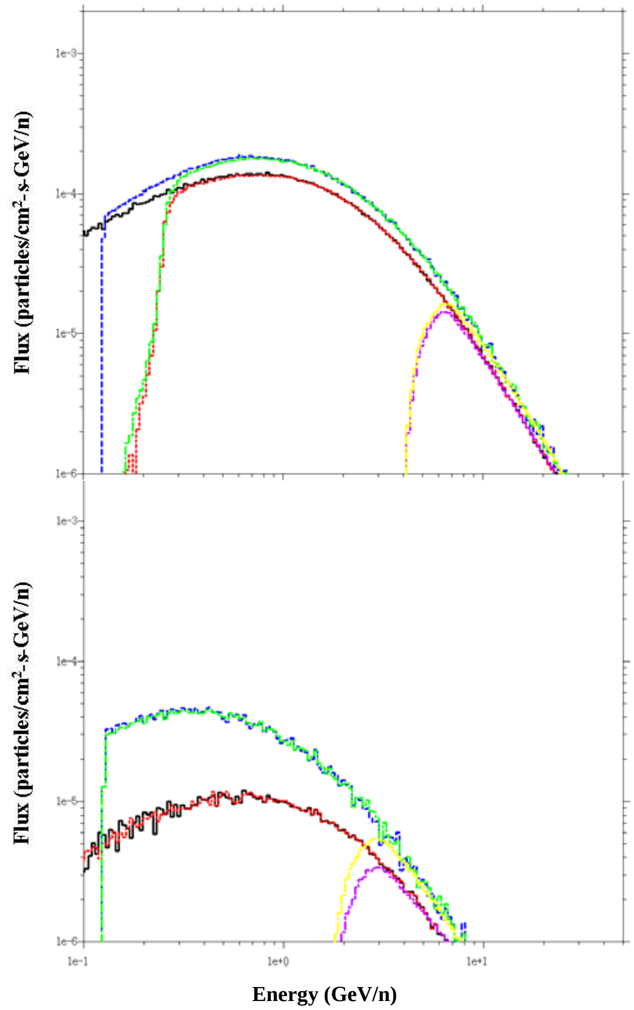

Fig. 2. Top figure gives the proton spectra for solar min. (1981) at 80°N (black=LEC, blue=BRI), 53°N (red=LEC, green=BRI), and 32°N (purple=LEC, yellow=BRI). Bottom figure gives the related alpha spectra at 80°N (black=LEC, blue=BRI), 53°N (red=LEC, green=BRI), and 32°N (purple=LEC, yellow=BRI).

MCNP6 User Interface

The user-interface for the new Cosmic-Source option involves an extension to one keyword on the SDEF card and the addition of two new keywords (see reference 4 for descriptions of input cards and keywords). A flag on the DBCN card can be used to force the use of the LEC source for terrestrial applications. Table II describes the new entries for these keywords. A negative sign on the PAR keyword indicates that the automatic normalization should be omitted, and the user should provide the desired normalization using the WGT keyword. As usual, latitude entries are relative to the equator and longitude entries are relative to Greenwich, UK. A zero value for the 32nd entry

Table II – Description of SDEF keywords.

Keyword	Values	Description
PAR	[-]cr	All cosmic particles
	[-]ch	Cosmic protons
	[-]ca	Cosmic alphas
DAT	M	Month (1-12)
	D	Day (1-31)
	Y	Year (4 digit)
LOC	P	Latitude (-90 to 90; S to N)
	A	Longitude (-180 to 180; W to E)
	H	Altitude (km)

on the DBCN card (the default) signifies: (1) use of LEC spectra when the LOC keyword is omitted from the SDEF card (i.e., interplanetary formulation), or (2) use of BRI spectra when the LOC keyword is specified (i.e., terrestrial formulation). A non-zero entry for this DBCN entry indicates use of LEC spectra even when the LOC keyword is specified.

Recommended Physics Options

In MCNP6, the cosmic-source spectra include a wide range of particle energies, from ~0.1 to ~1,000 GeV/n. Interactions of these high-energy particles with atmosphere or regolith materials requires physics treatments that span ~15 orders of magnitude in energy and include nearly an exhaustive list of stable target nuclei. This challenge is met in MCNP6 with the use of library physics for low-energy interactions (E<~150 MeV) and the use of model physics for intermediate- and high-energy interactions. For the intermediate-energy regime (~150-3500 MeV), four intra-nuclear cascade (INC) physics models are available (Bertini, ISABEL, INCL, CEM), and for the high-energy regime there are two models available (FLUKA, LAQGSM). The model options and transition energies can be specified on the LCA, LCB, LEA, and LEB cards of the input file.

For cosmic-source applications, we currently recommend the use of ENDF/B-VII library data and the CEM INC model, coupled with the LAQGSM high-energy model. These model physics packages are not the defaults and should be specified using the 9th and 10th entries on the LCA card. We also recommend that the model transition energies, specified on the LCB card, should be reduced from their default values to ~1000 MeV.

RESULTS

One approach to benchmarking the new MCNP6 cosmic-source spectra is to compare secondary neutron spectra to measured data taken aboard NASA ER-2 aircraft in June 1997 [9]. The measurements reported in reference 9 have been reanalyzed for this comparison, but the results did not change substantially. Using the LEC and BRI source options combined with a 300-region MCNP atmospheric model developed by BRI, along with the most recent BRI sky-map data and the MCNP6 physics options discussed above, we have calculated secondary neutron flux spectra on surfaces that closely match the ER-2 coordinates during neutron data collection.

Fig. 3 presents a comparison of these calculated spectra to measured data at 16.4 km (or 101 g/cm^2 in atmospheric depth) above a location in western Canada. Similarly, Figs. 4 and 5 provide a comparison to measurements at ~20 km (~55 g/cm^2) for two very different latitudes (one over Canada and one west of Mexico). The calculated and measured spectra are in very good agreement (<10%), especially since the experimental uncertainty around the high-energy peak is ~20% [10]. It is important to note that MCNP6 automatic normalizations were used for these calculations and no post-processing adjustments were made to the spectra.

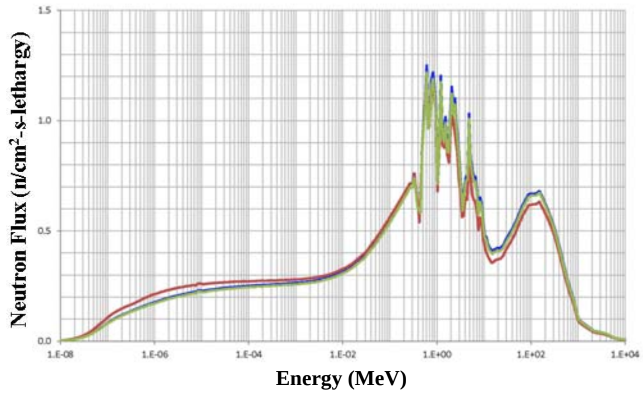

Fig. 3. Calculated neutron spectra (LEC=blue, BRI= green) and measured spectra (red) at 56°N, 121°W, and 16.4 km (101 g/cm^2).

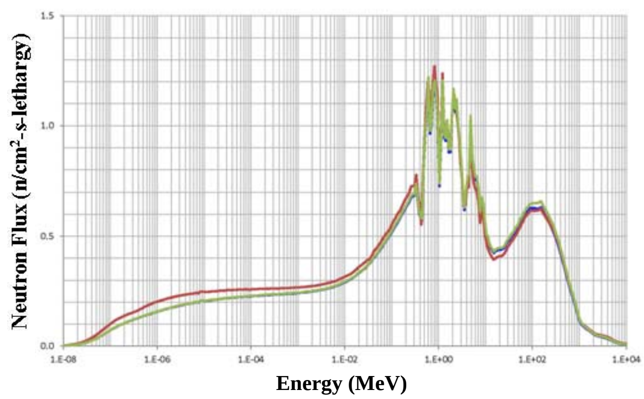

Fig. 4. Calculated neutron spectra (LEC= blue, BRI= green) and measured spectra (red) at 54°N, 117°W, and 20.2 km (56.0 g/cm^2).

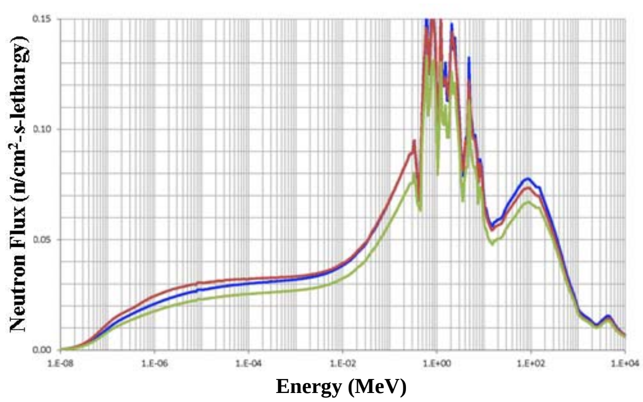

Fig. 5. Calculated neutron spectra (LEC= blue, BRI= green) and measured spectra (red) at 19°N, 127°W, and 20.3 km (53.5 g/cm^2).

The slight differences in these spectra at high energy are likely due to approximations in the CEM and LAQGSM physics models. Differences in the epithermal energy range are likely due to the limited number of atmospheric regions and limited isotopics (i.e., omission of rare gases and pollutants).

ENDNOTES

We acknowledge the sponsorship of DHS/DNDO for this work.

REFERENCES

1. D. B. PELOWITZ, editor, "MCNPX User's Manual, Version 2.5.0," LANL report LA-CP-05-0369 (2005).
2. D. B. PELOWITZ, editor, "MCNPX User's Manual, Version 2.6.0," LANL report LA-CP-07-1473 (2008).
3. D. B. PELOWITZ, editor, "MCNPX User's Manual, Version 2.7.0," LANL report LA-CP-11-0438 (2011).
4. D. B. PELOWITZ, editor, "MCNP6 User's Manual, Beta Release" LANL report LA-CP-11-1708 (2011).
5. G. C. CASTAGNOLI and D. LAL, "Solar Modulation Effects in Terrestrial Production of Carbon-14," *Radiocarbon*, **22**, No. 2, 133-158 (1980).
6. J. M. CLEM, G. DE ANGELIS, P. GOLDHAGEN, and J. W. WILSON, "New Calculations of the Atmospheric Cosmic Radiation Field – Results for Neutron Spectra," *Radiation Protection Dosimetry*, **110**, pp. 423-428 (2004).
7. J. MASARIK and R. C. REEDY, "Gamma ray Production and Transport in Mars," *J. Geophys. Res.*, **101**, 18,891-18,912 (1996).
8. D. LAL, "Theoretically Expected Variations in the Terrestrial Cosmic-Ray Production Rates of Isotopes," *Proc. of the Inter. School of Physics*, Course XCV, Solar-Terrestrial Relationships and the Earth Environment in the last Millennia, G. C. Castagnoli ed., 216-233 (1985).
9. P. GOLDHAGEN, J. M. CLEM, and J. W. WILSON, "The Energy Spectrum of Cosmic-Ray Induced Neutrons Measured on an Airplane Over a Wide Range of Altitude and Latitude," *Radiation Protection Dosimetry*, **110**, pp. 387-392 (2004).
10. P. GOLDHAGEN, "An Extended-Range Multisphere Neutron Spectrometer with High Sensitivity and Improved Resolution," *Nuclear Technology*, **175**, pp. 81-88 (2011).